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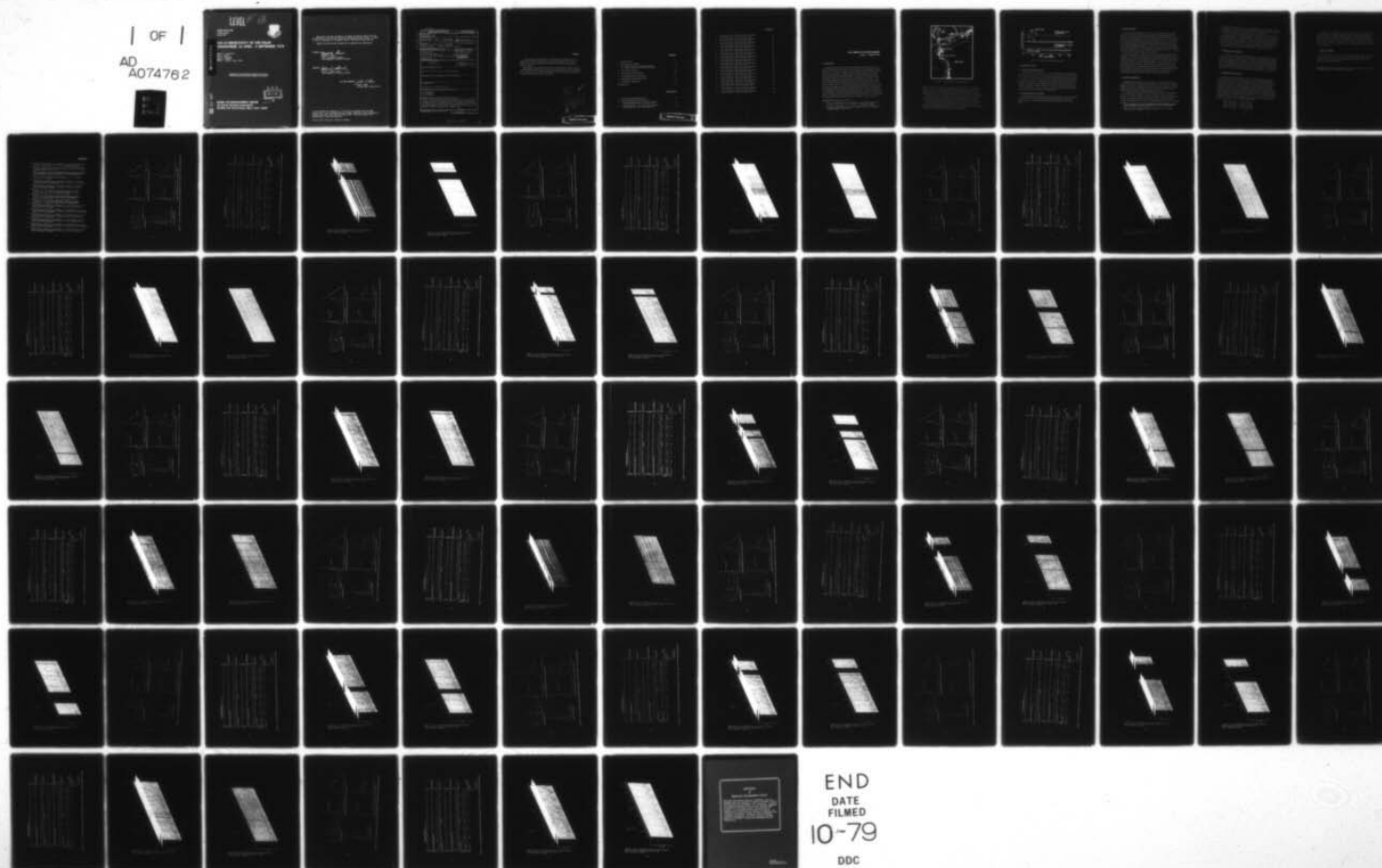
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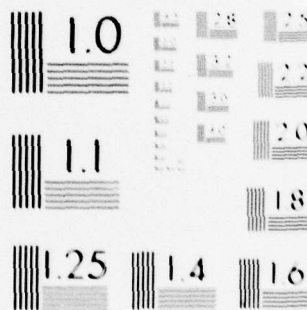
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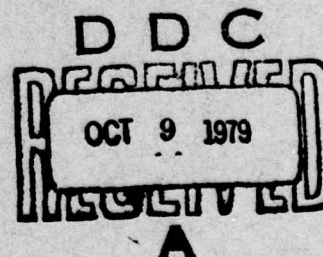
March 1979



**VLF/LF REFLECTIVITY OF THE POLAR
IONOSPHERE, 23 APRIL - 2 SEPTEMBER 1978**

Robert P. Pagliarulo
John P. Turtle
John E. Rasmussen
Wayne I. Klemetti
Robert L. Cooley, TSgt, USAF

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Preface

The authors thank in particular Mr. Duane Marshall of Megapulse, Inc., for help with the equipment that made the measurements possible, and Mr. Bjarne Ebbesen of the Danish Meteorological Institute for the outstanding operation at Qanaq, Greenland.

Appreciation is also extended to the Danish Commission for Scientific Research in Greenland for allowing these measurements to be conducted and to Jorgen Taagholt and V. Neble Jensen of the Danish Meteorological Institute's Ionospheric Laboratory for their continued cooperation in this program.

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VLF/LF Reflectivity of the Polar Ionosphere

23 April - 2 September 1978

1. INTRODUCTION

This report provides a summary of high latitude ionospheric reflectivity, as observed by the USAF's high resolution VLF/LF ionosounder operating in northern Greenland.^{1,2} As shown in Figure 1, the transmitter is located at Thule Air Base, Greenland (76° 33'N. Lat., 68° 40'W. Long.), and the receiving site is 106 km north at the Danish Meteorological Institute's Ionospheric Observatory in Qanaq, Greenland (77° 24'N. Lat., 69° 20'W. Long., Geomagnetic Lat. 89° 06'N). The ionosounding transmissions consist of a series of extremely short (approximately 100 μ sec) VLF pulses, precisely controlled in time, and radiated from a 130 m vertical antenna. At the receiving site, orthogonal loop antennas are used to separate the two polarization components of the ionospherically reflected skywave signal. One antenna, oriented in the plane of propagation, is used to sense the groundwave and the "parallel" component of the downcoming skywave. The second loop, nulled on the groundwave, senses the "perpendicular" skywave component. The signal from each of the antennas is digitally averaged to improve the signal-to-noise ratio of the individual received waveforms before they are recorded on magnetic tape. An

(Received for publication 29 March 1979)

1. Lewis, E. A., Rasmussen, J. E., and Kossey, P. A. (1973) Measurements of ionospheric reflectivity from 6 to 35 kHz, J. Geophys. Res. 78:19.
2. Kossey, P. A., Rasmussen, J. E., and Lewis, E. A. (1974) VLF pulse ionosounder measurements of the reflection properties of the lower ionosphere, Akademie Verlag, COSPAR, July.



Figure 1. Geometry of the Propagation Path

example of the observed waveforms is given in Figure 2, where the "parallel" waveform (Figure 2a) consists of a groundwave propagated pulse, a quiet interval containing low level, off path groundwave reflections, followed by the first-hop parallel skywave component. The perpendicular waveform is shown in Figure 2b.

Ionospheric reflection parameters are derived by computer (AFGL's CDC 6600) processing of the ground and ionospherically reflected waveforms with allowance made for factors such as ground conductivity and antenna patterns (see Section 4).

Although the data are recorded about once per minute, for this report the waveforms are averaged into 2-hr time blocks with the exception of the three-dimensional waveform presentations (Section 2.2). The resulting information is presented in a weekly format (Figures 3 through 21 as described below).

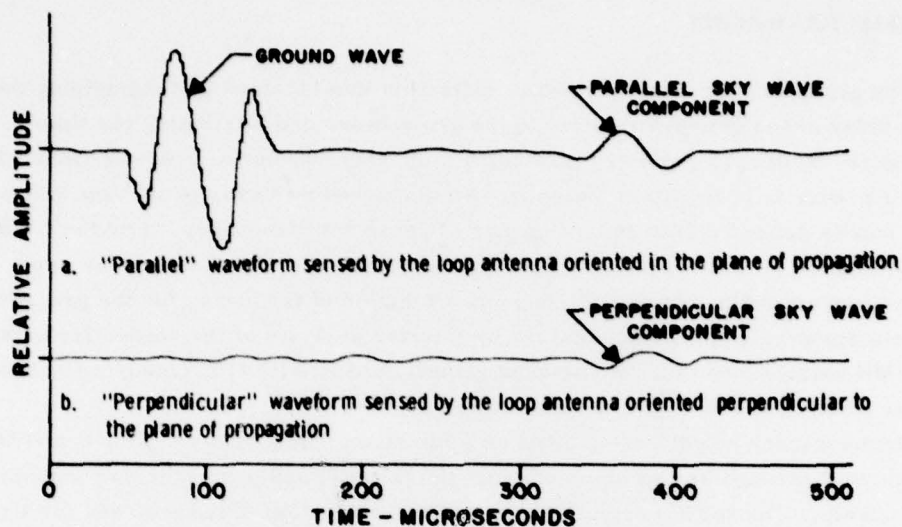


Figure 2. Example of the Observed Waveforms

2. OBSERVED WAVEFORMS

2.1 Weekly Example of Individual Waveforms

In part A of Figures 3 through 21, a set of averaged parallel and perpendicular waveforms is presented for the time block centered near local noon of the indicated day. Each of these waveforms is comprised of 256 digitally averaged points spaced 2 μ sec apart. In part B of the figures, the groundwave Fourier amplitudes are shown as a function of frequency. Although the data presented in parts C through L of the figures are generally limited to frequencies in the first, or principal, lobe of the spectrum, information at higher frequencies can be used when sufficient signal-to-noise conditions exist. There is, however, a frequency range around each spectral null where insufficient signal exists for measurements.

2.2 Three-Dimensional Waveform Presentation

A three-dimensional display of the recorded \parallel waveforms covering each weekly period is shown in Part R of each figure and the corresponding \perp waveforms are shown in Part S. For these plots the data has been averaged into 15-min time blocks.

3. REFLECTION HEIGHTS

The group mirror height (GMH) of reflection was obtained by determining the group delay of the skywave relative to the groundwave and attributing the time difference, by simple geometry (assuming a sharply bounded mirror-like ionosphere) to a difference in propagation distance. As discussed by Lewis et al,¹ the group delay can be defined as the rate of change of phase with frequency. For the GMH data presented in this report, a finite frequency difference of 1.0 kHz was used, and the corresponding phase difference as a function of frequency for the groundwave and both skywave signals was obtained by Fourier analysis of the respective pulses. The GMH calculations took into account ground conductivity (10^{-3} mho/m is assumed), and the corrections of Wait and Howe³ were applied.

Group mirror heights are plotted as a function of frequency in parts C and D of Figures 3 through 21, as obtained from the parallel and perpendicular waveforms, respectively. The GMH's are also presented as a function of time-of-day for the average frequency of 16.5 kHz in figure parts E and I. The parallel GMH's in part E are shown along with an average reflection height for reference purposes. Each point of the reference height is a weekly average, by time block, for the 7-day period indicated. The corresponding perpendicular GMH's, part I of the figures, are also shown with the weekly average for comparison. Part G gives the average, by time block, for the daily parallel GMH data of part E, and part K gives the corresponding perpendicular GMH averages from the daily data of part I.

4. REFLECTION COEFFICIENTS

Assuming that the ionosphere acts as a "mirror" at the GMH, plane wave reflection coefficients⁴ were obtained by comparing the ratio of the skywave Fourier amplitude at a specific frequency to that of the groundwave, taking into account the antenna patterns, wave spreading, earth curvature, ground conductivity, path lengths, and antenna patterns including ground image effects.

The reflection coefficient $||R||$ was obtained from analysis of the parallel sky-wave component and is plotted as a function of frequency in part C of Figures 3 through 21. The $||R||$ coefficient for 16 kHz is plotted as a function of time-of-day in part F along with the average of the indicated week for reference purposes. From the perpendicular skywave pulse, the coefficient $||R_{\perp}||$ was obtained and appears

3. Wait, J. R., and Howe, H. H. (1956) Amplitude and Phase Curves for Ground-Wave Propagation in the Band 200 Cycles per Second to 500 Kilocycles, Nat. Bur. Stand. U.S. Circ. No. 574.

4. Budden, K. G. (1961) Radio Waves in the Ionosphere, p. 85, Cambridge University Press, London.

as a function of frequency in part D. The 16 kHz HR_{\perp} is shown along with its reference in part J. Parts H and L present the average, by time block, of the daily HR_{\parallel} and HR_{\perp} data which are presented in parts F and J, respectively.

For certain coefficient data points, plotted as asterisks (*), the reflection coefficient appears without a corresponding GMH. For these particular data, only the skywave-groundwave ratios could be obtained as the skywaves were too weak to provide reliable group delay information. The reflection coefficients were therefore estimated using a nominal GMH of 80 km in the calculations. These estimated coefficient values are included in the averages presented in parts H and L, but the assumed heights are not used in the GMH averages shown in parts G and K.

5. SUPPLEMENTARY INFORMATION

For purposes of comparison and interpretation, certain supplementary data are presented. Part M of the figures shows the magnitude of the horizontal component of the polar magnetic field as recorded on a three-axis fluxgate magnetometer and part N presents 30-MHz riometer data, an indicator of D-region particle precipitation. These supplementary data were recorded at 30-sec intervals by RADC/EEP at Thule AB; the curves represent the average of 10-min periods. The solar zenith angle is given in part O of Figures 3 through 21 for the indicated mid-week date.

6. IONOSPHERIC DISTURBANCE DATA

The period covered by this report contained the largest number of energetic particle disturbances that have occurred since VLF/LF ionosounding operations began at Thule AB in 1974. The report begins during a Polar Cap Absorption (PCA) event that had started on 16 April (DAY 106). The entire period from 16 April (DAY 106) to 15 May (DAY 136) shows lowered reflection heights as one particle event after another occurred. The strongest event occurred on 30 April (DAY 120). During this event the riometer indicated a maximum of about 7 dB absorption and the parallel group reflection height dropped to approximately 55 km. Subsequent events were recorded on 7 May (DAY 127) and 11 May (DAY 131). Final recovery to normal propagation conditions did not occur until 15 May (DAY 136). The effects of other particle events can be seen during the following periods.

31 May (DAY 151) —	4 June (DAY 155)
9 June (DAY 160) —	11 June (DAY 162)
23 June (DAY 174) —	29 June (DAY 180)
11 July (DAY 192) —	19 July (DAY 200)

In addition to the energetic particle events the effects of solar x-ray flares can be seen in the data. A Sudden Ionospheric Disturbance (SID) which results from a solar flare can be seen in the 3-D waveform plots as a rapid drop in reflection height followed by a slower recovery. The SID usually lasts from about 30 min to 2 or 3 hours. Many flare related SIDS can be seen in this period, especially from 19 May (DAY 139) - 5 June (DAY 156). A particularly large SID occurred on 11 July (DAY 192).

7. ADDITIONAL COMMENTS

This report is one of a series.⁵⁻¹⁵ Comments and suggestions for improving its usefulness should be addressed to the Propagation Branch (EEP), Electromagnetic Sciences Division, Deputy for Electronic Technology (RADC/EEP), Hanscom AFB, Massachusetts 01731.

(Because of the large number of references cited above, they will not be listed here. See Reference Page 13, for References 5 through 15.)

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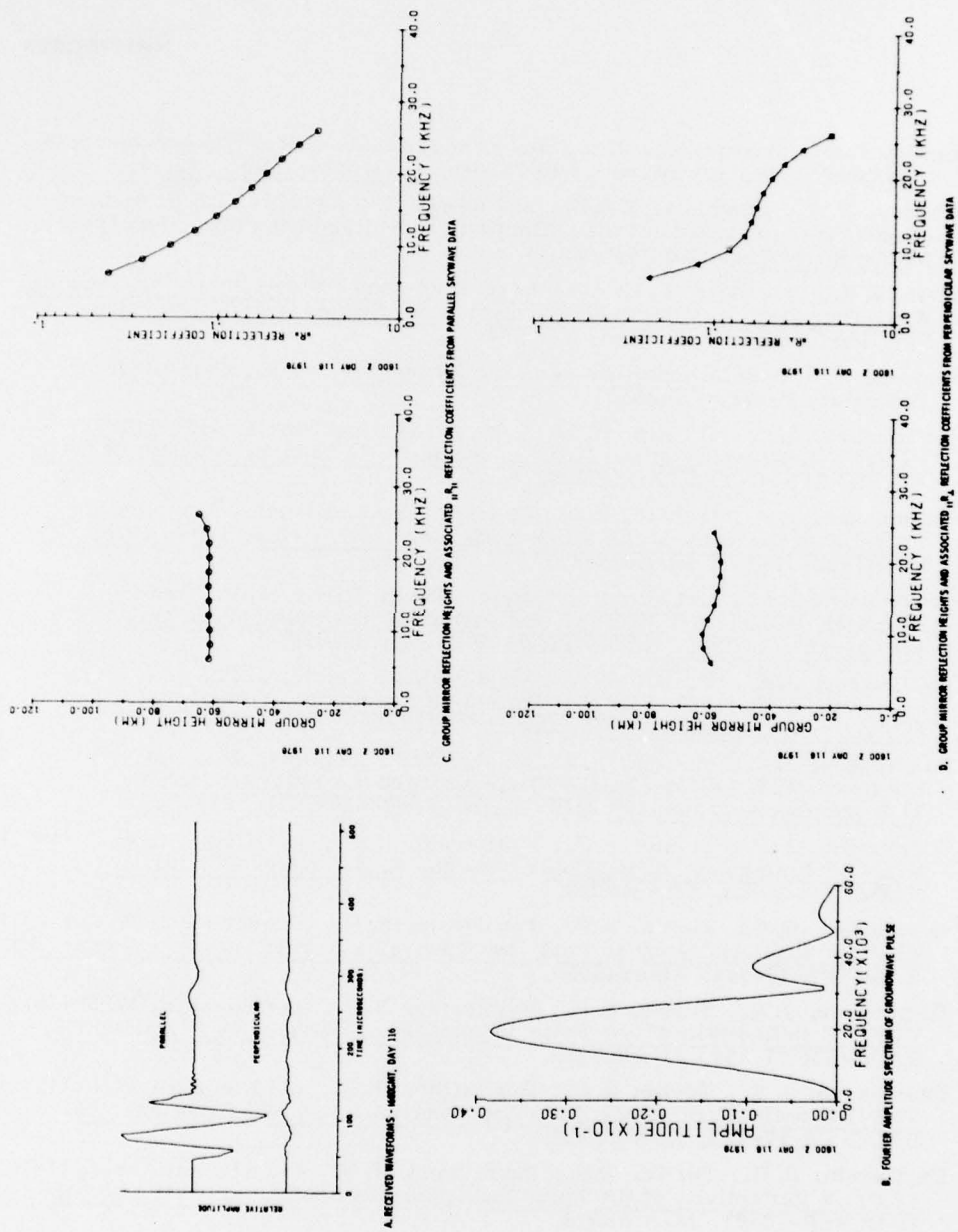


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 113 (23 Apr) - DAY 119 (29 Apr) 1978

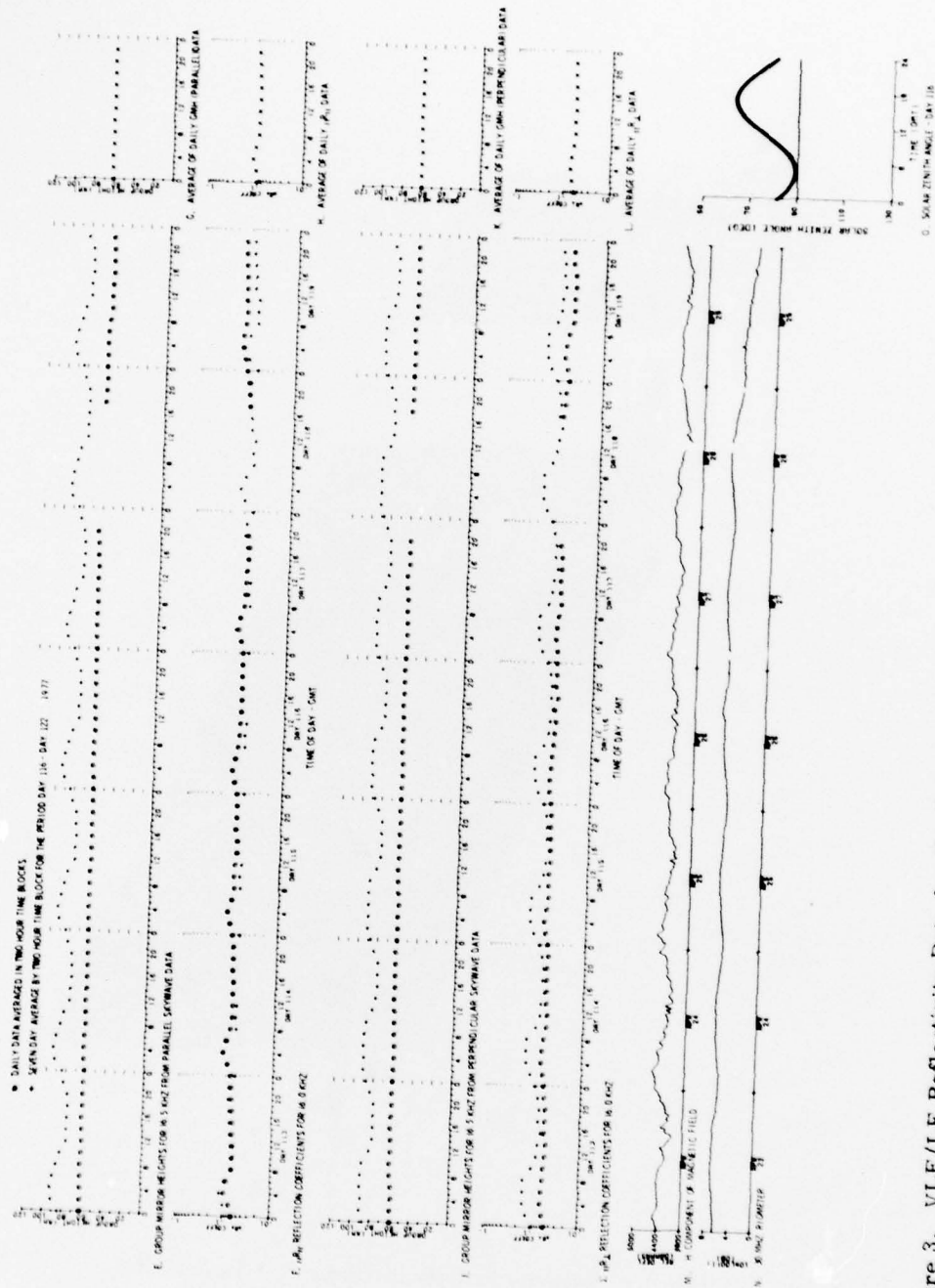


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 113 (23 Apr) - DAY 119 (29 Apr) 1978 (Cont)

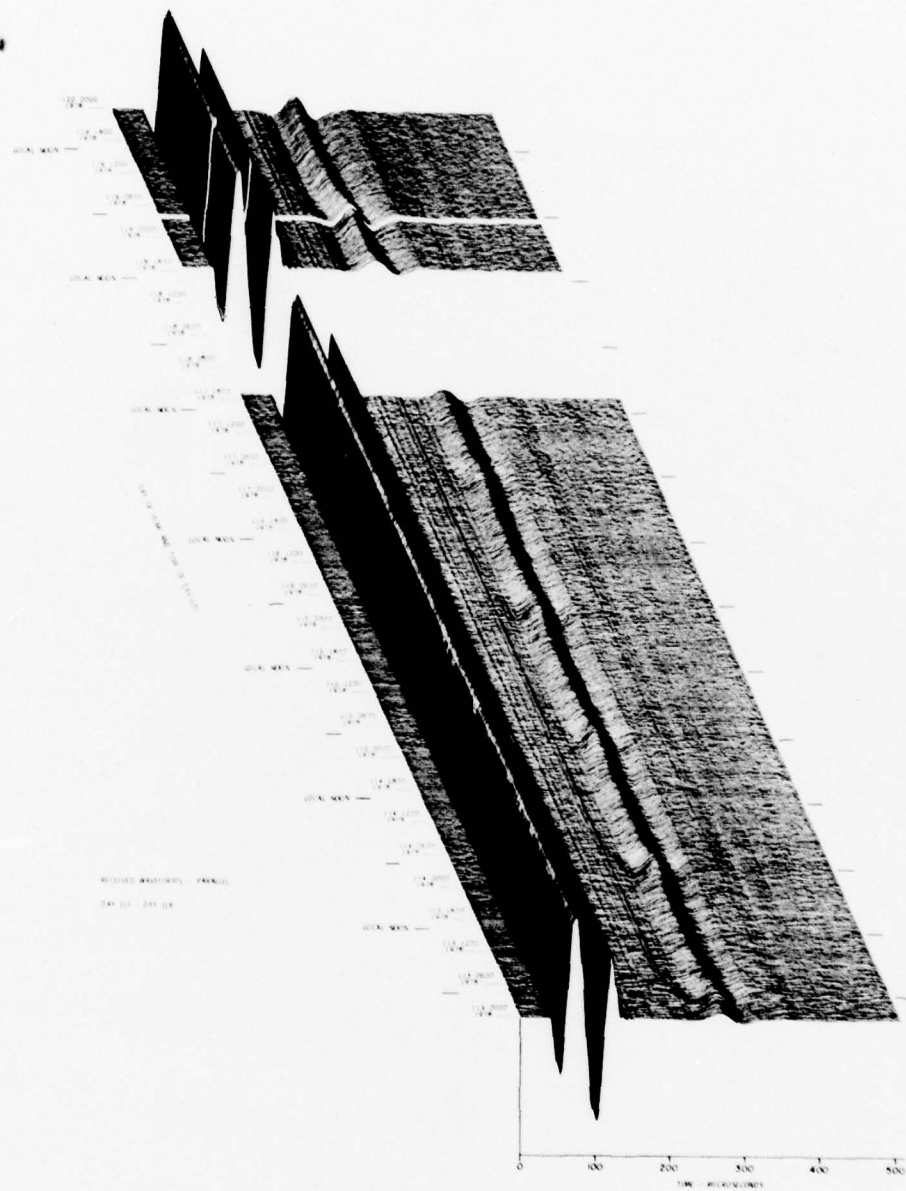


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 113 (23 Apr) - DAY 119 (29 Apr) 1978 (Cont)
 Part R. || Waveform Display

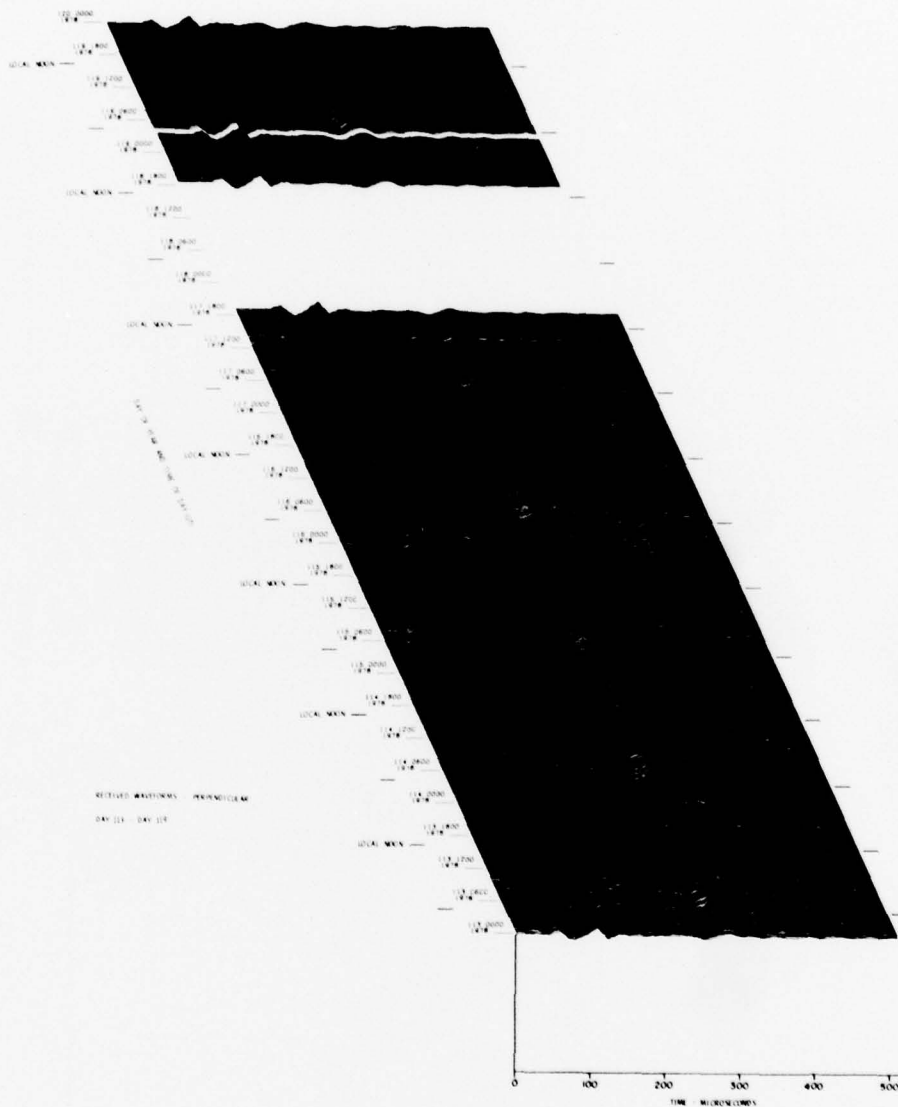


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere,
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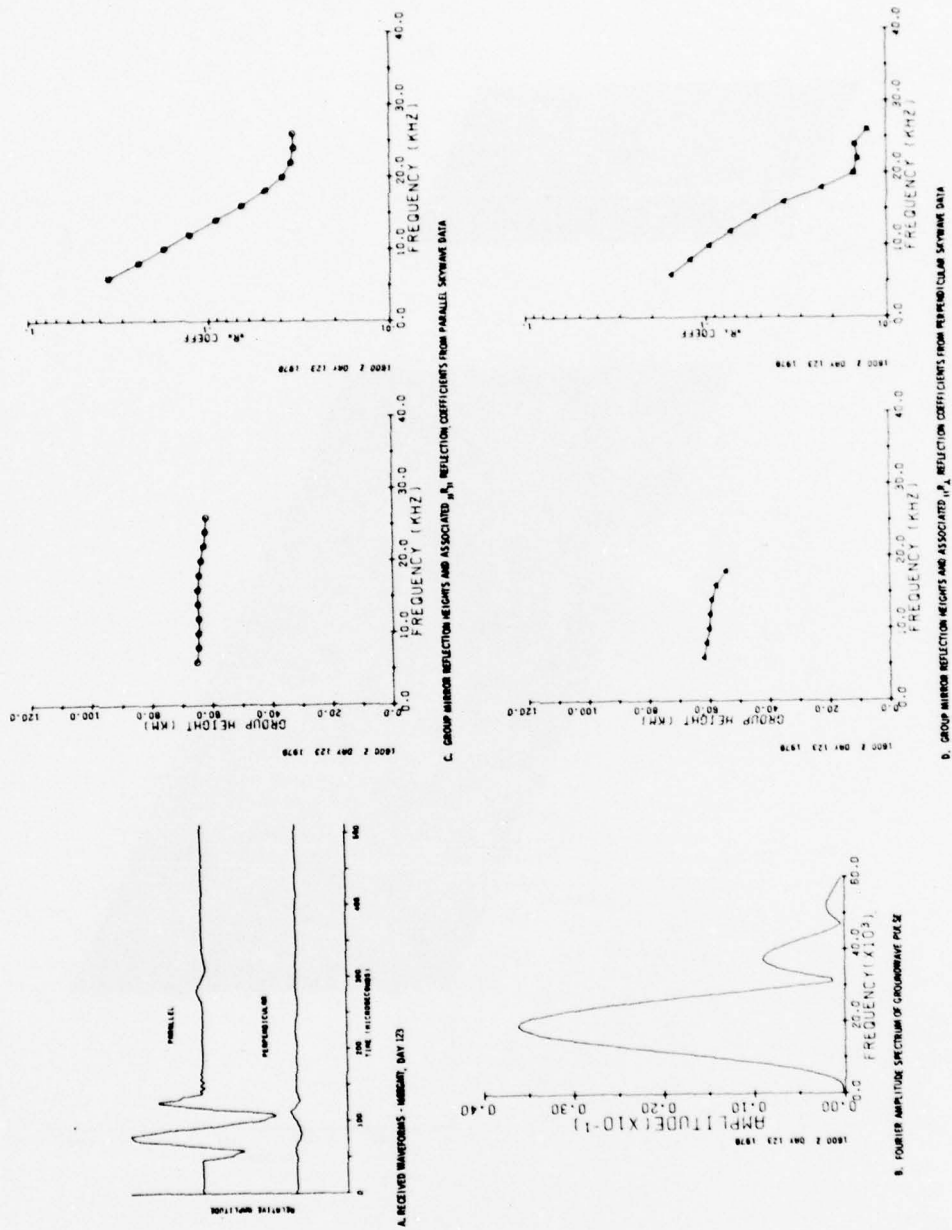


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 120 (30 Apr) - DAY 126 (6 May) 1978

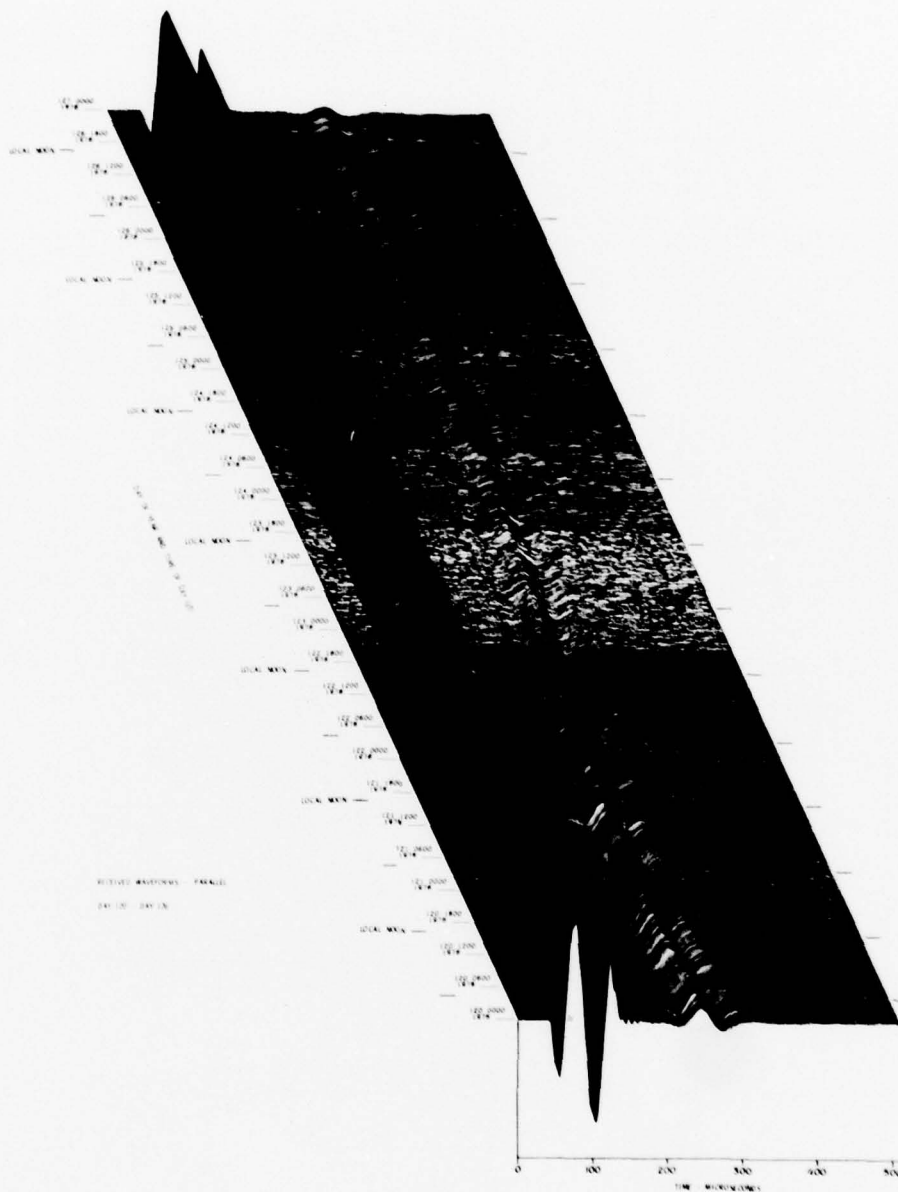


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere,
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 Part R. || Waveform Display

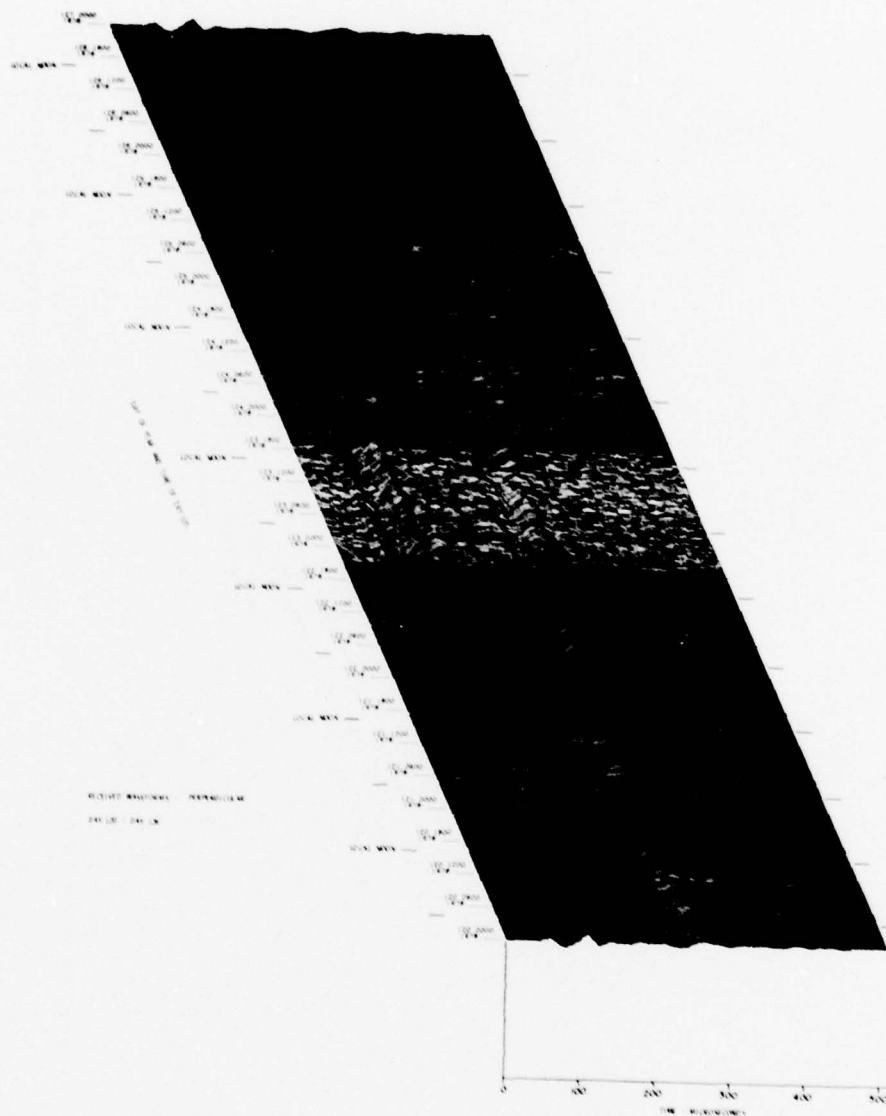


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere,
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 Part S. 1 Waveform Display

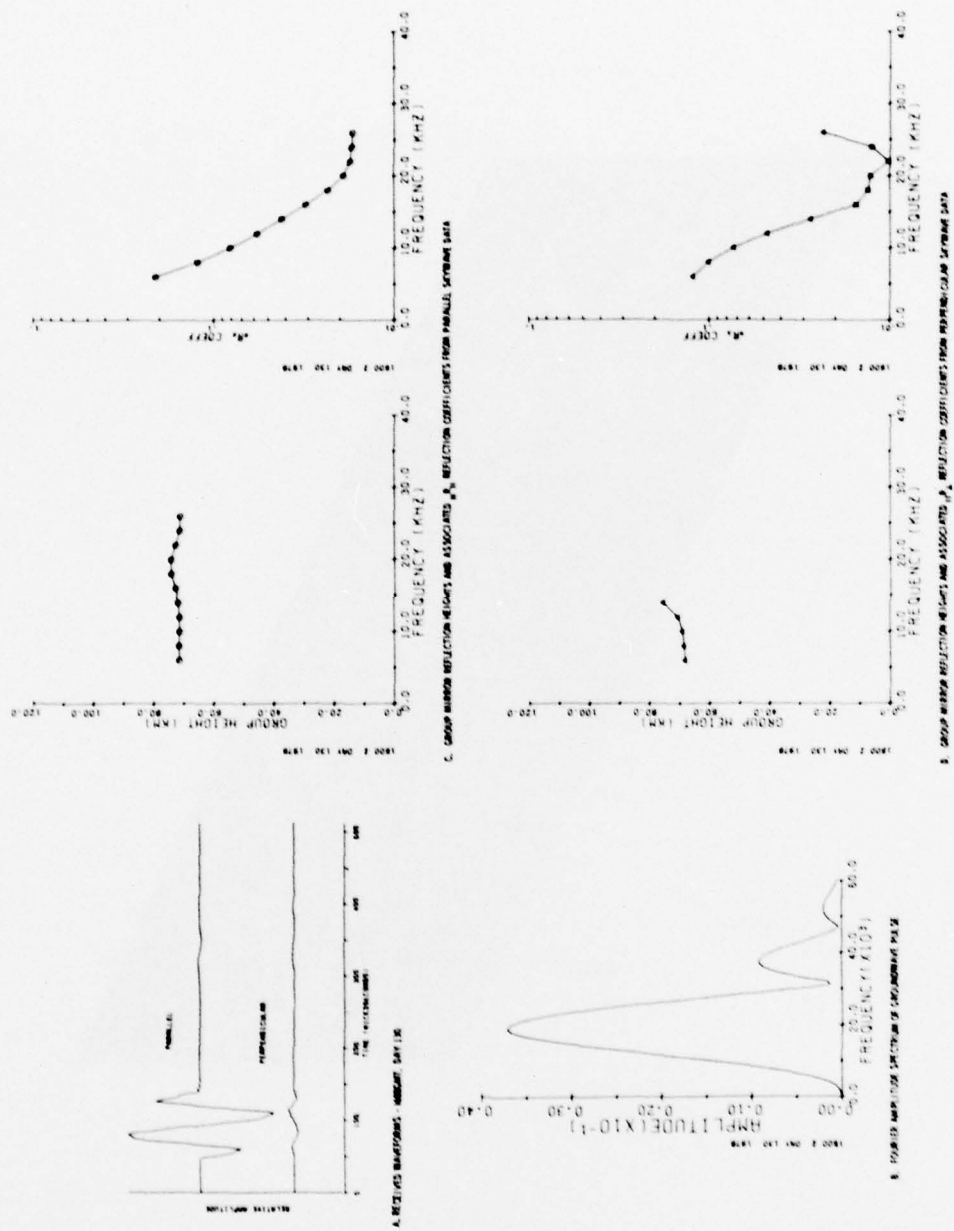


Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 127 (7 May) - DAY 133 (13 May) 1978

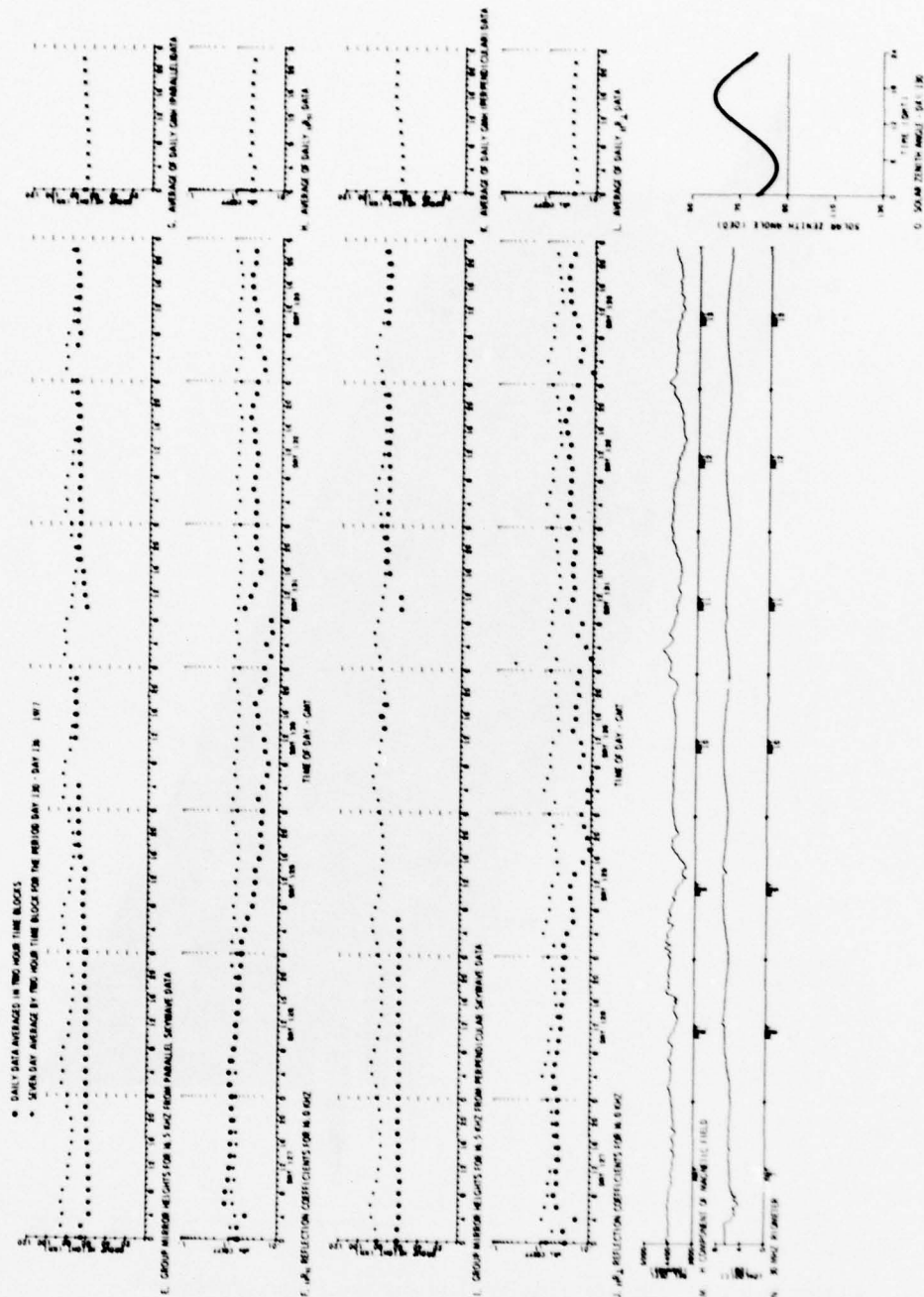


Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 127 (7 May) - DAY 133 (13 May) 1978 (Cont)



Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 127 (7 May) — DAY 133 (13 May) 1978 (Cont)
 Part R. II Waveform Display



Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 127 (7 May) - DAY 133 (13 May) 1978 (Cont)
 Part S. \perp Waveform Display

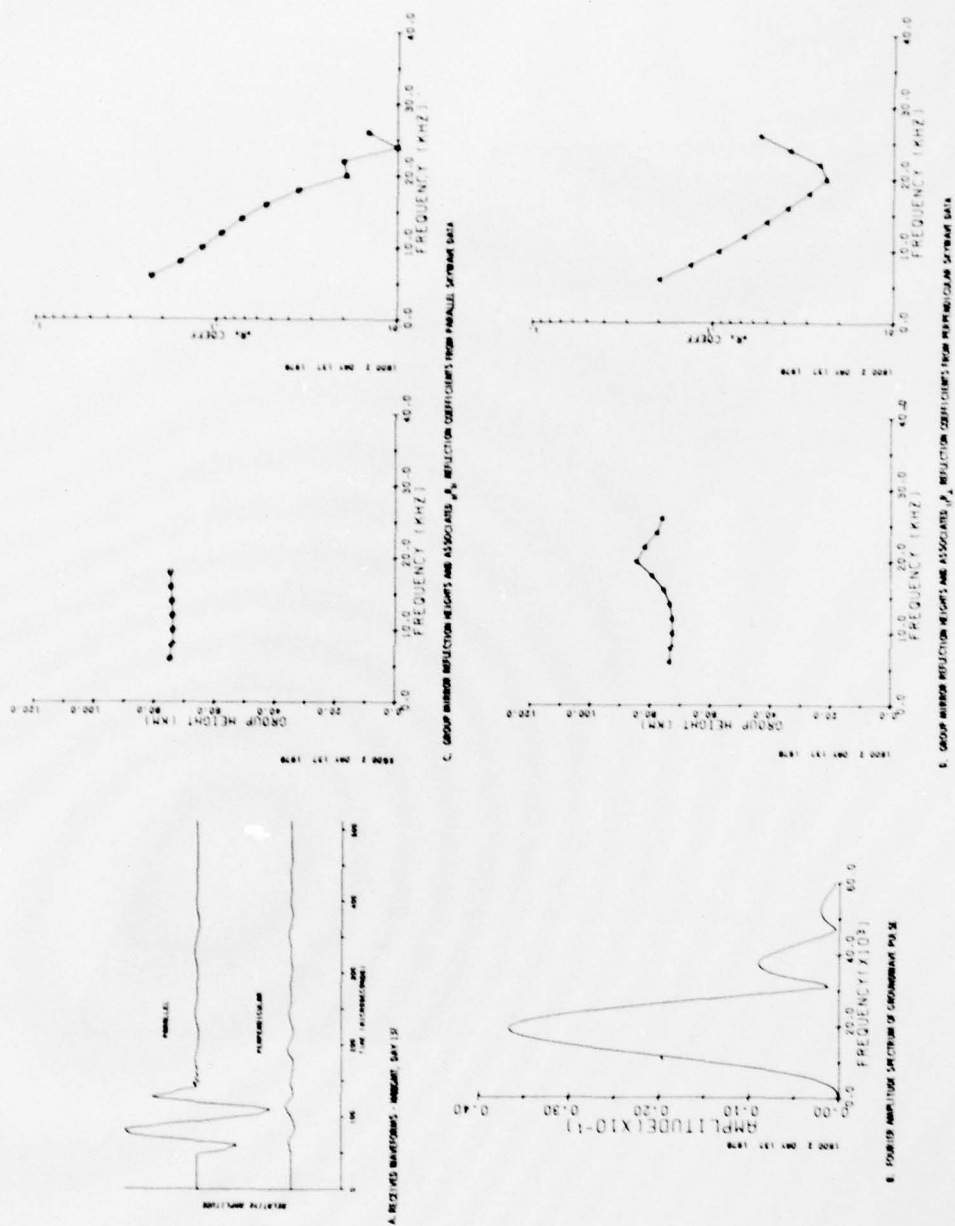


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 134 (14 May) - DAY 140 (20 May) 1978

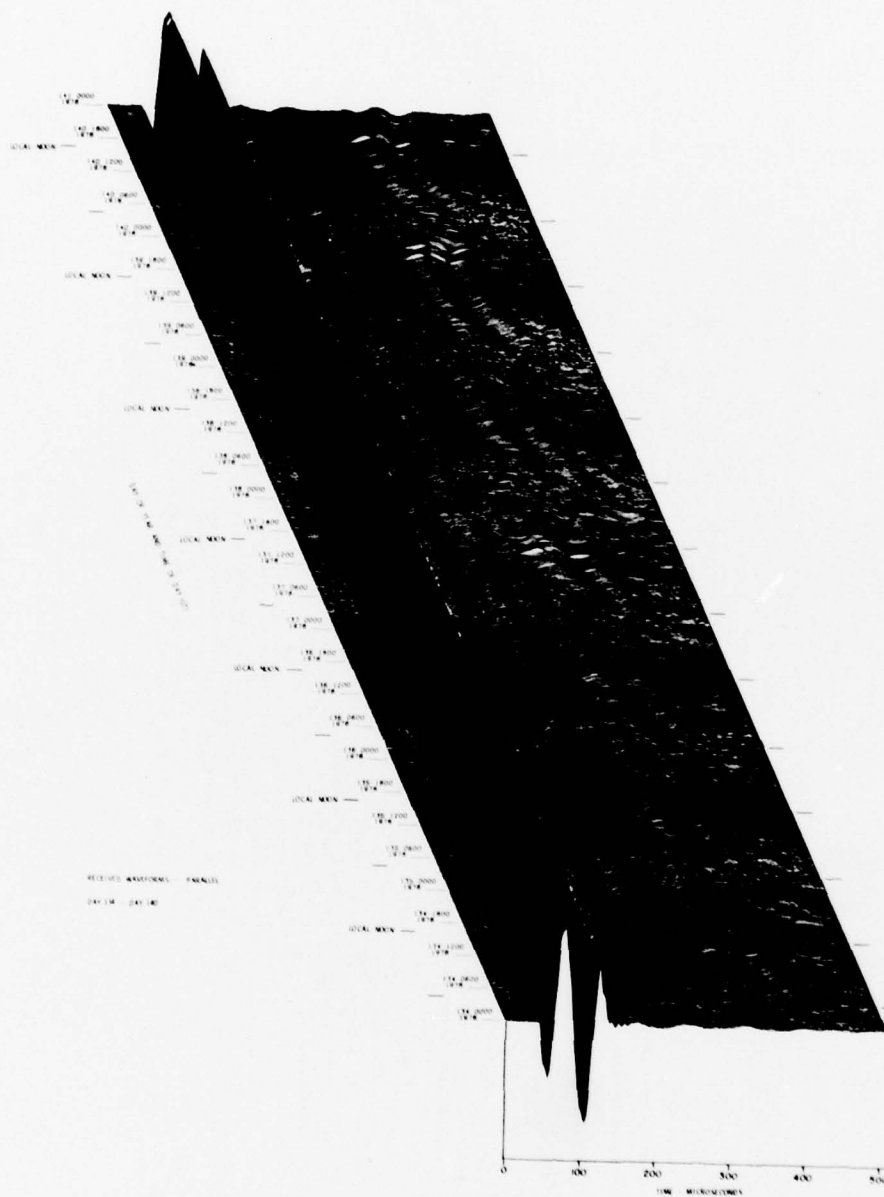


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 134 (14 May) - DAY 140 (20 May) 1978 (Cont)
 Part R. II Waveform Display

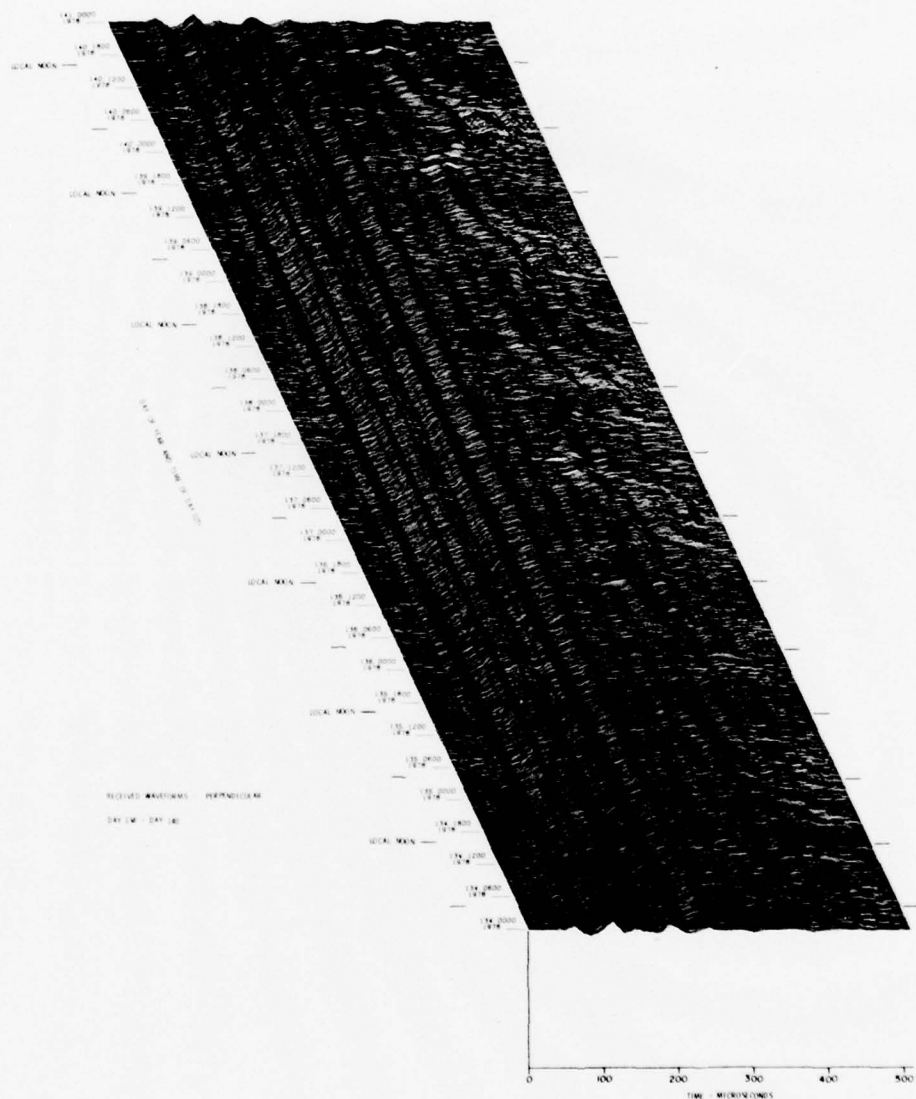


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 134 (14 May) - DAY 140 (20 May) 1978 (Cont)
Part S. \perp Waveform Display

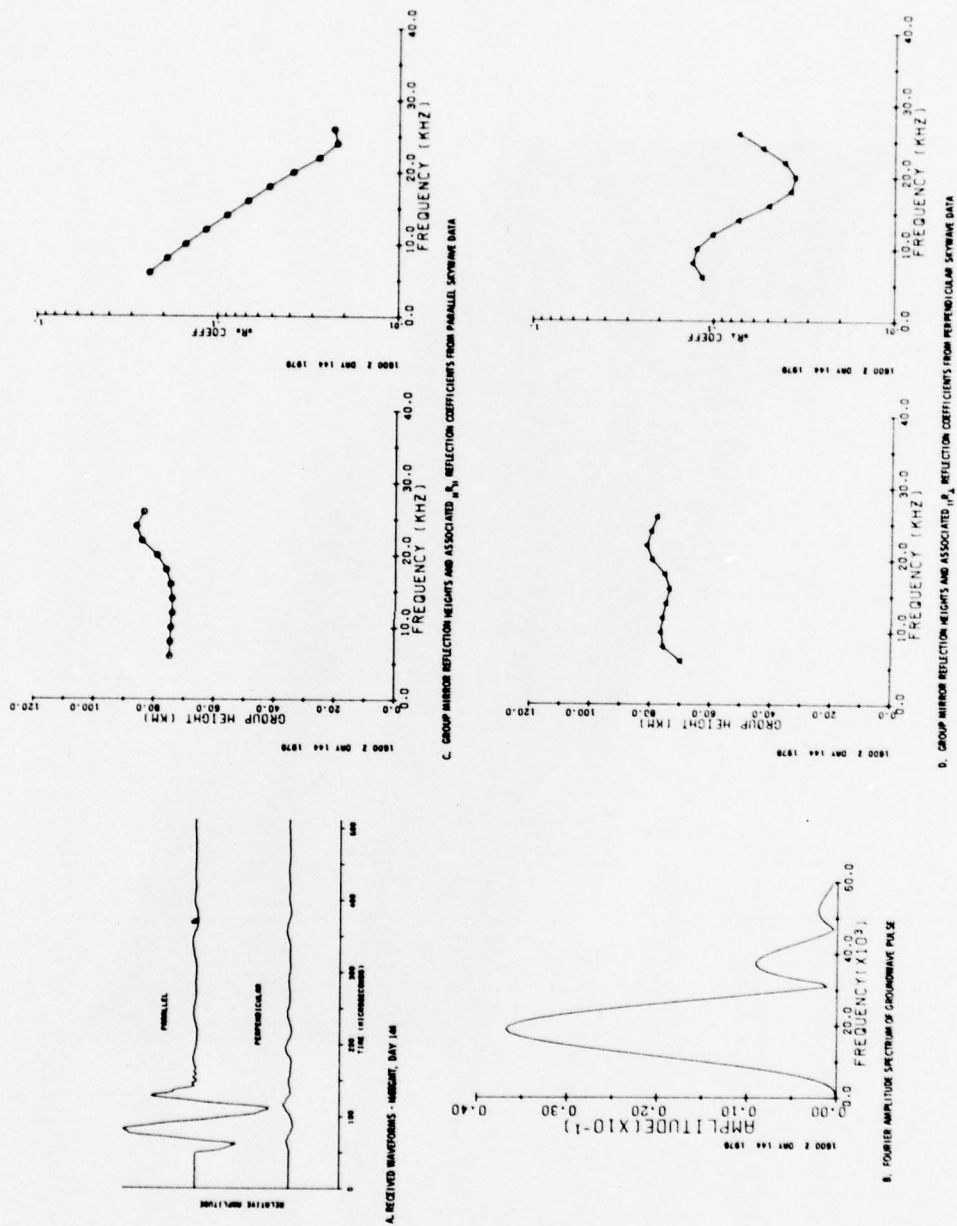


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 141 (21 May) - DAY 147 (27 May) 1978

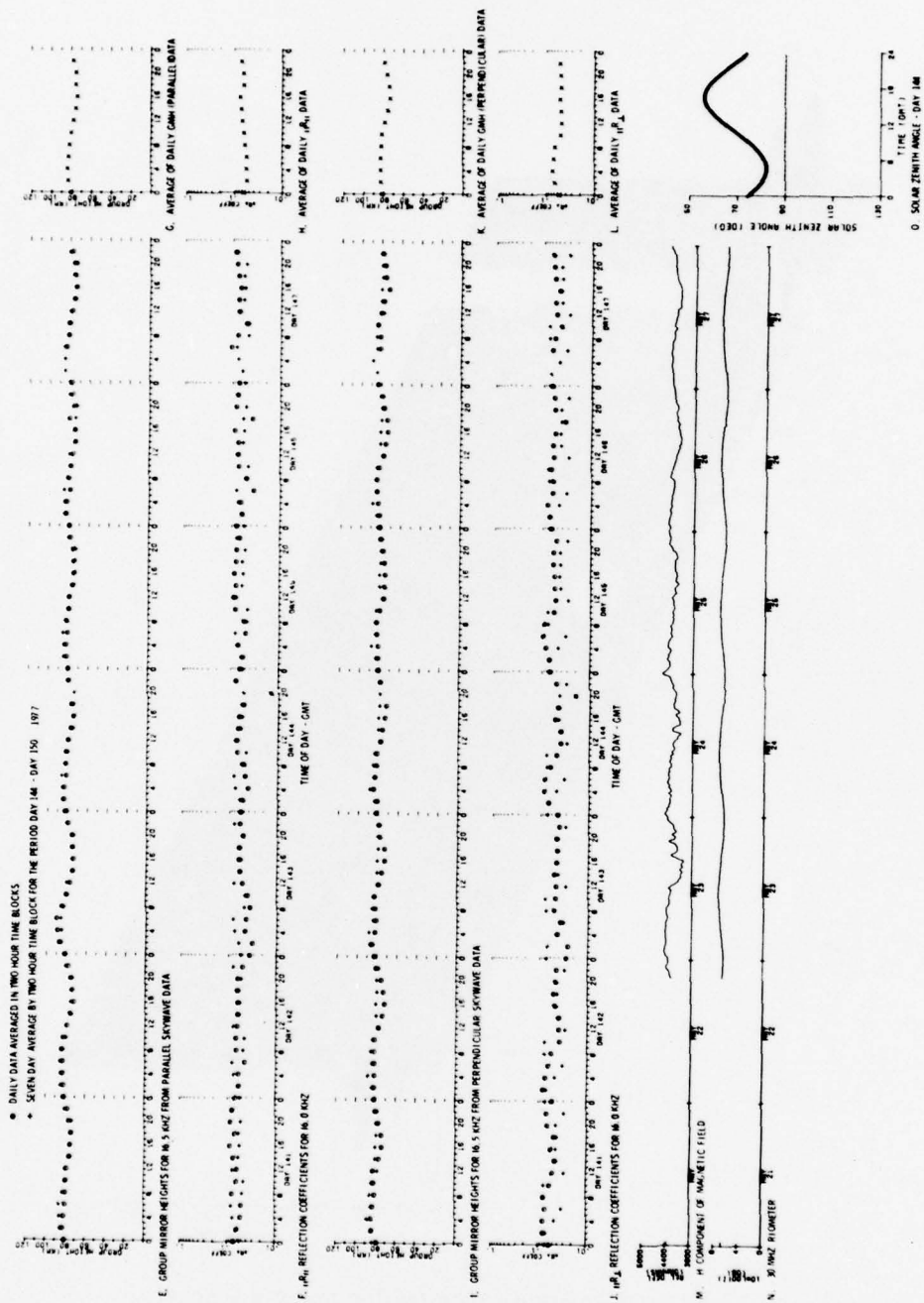


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 141 (21 May) - DAY 147 (27 May) 1978 (Cont)

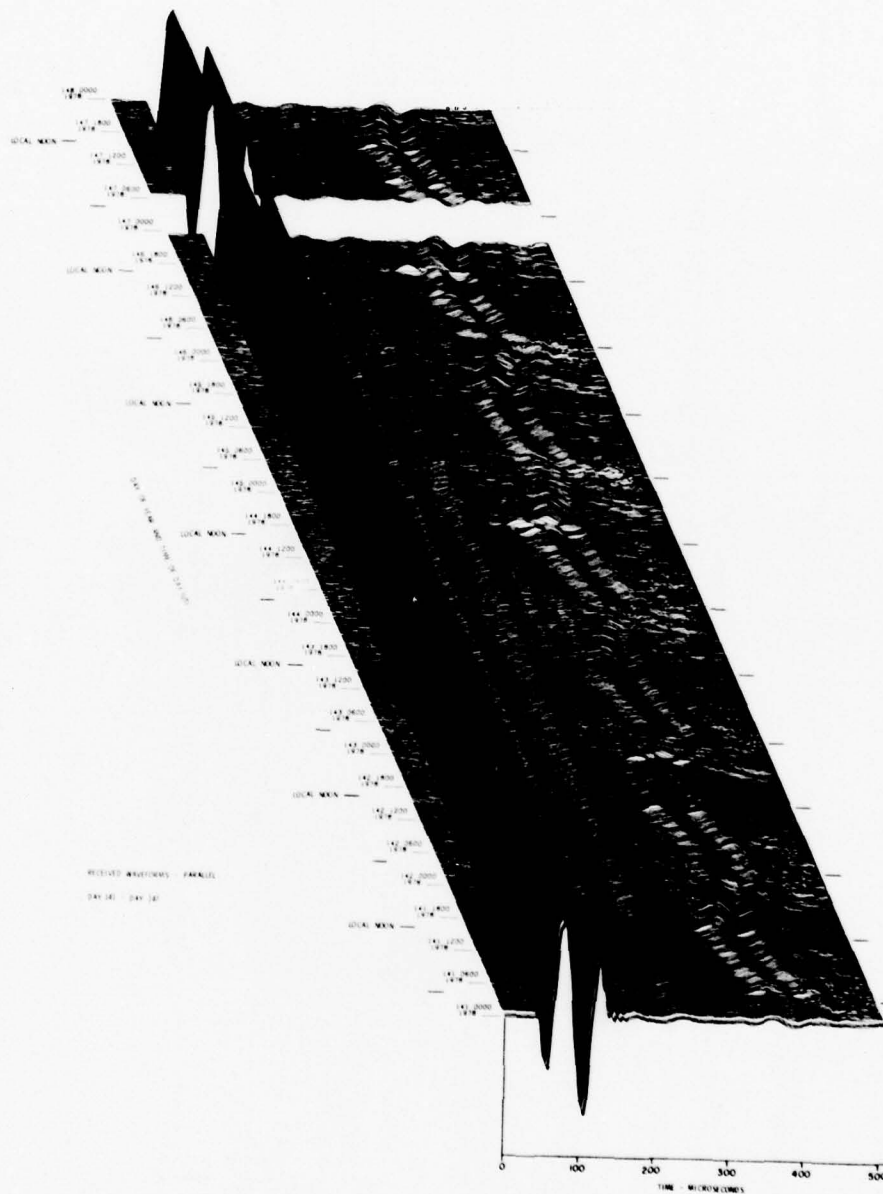


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 141 (21 May) - DAY 147 (27 May) 1978 (Cont)
 Part R. || Waveform Display

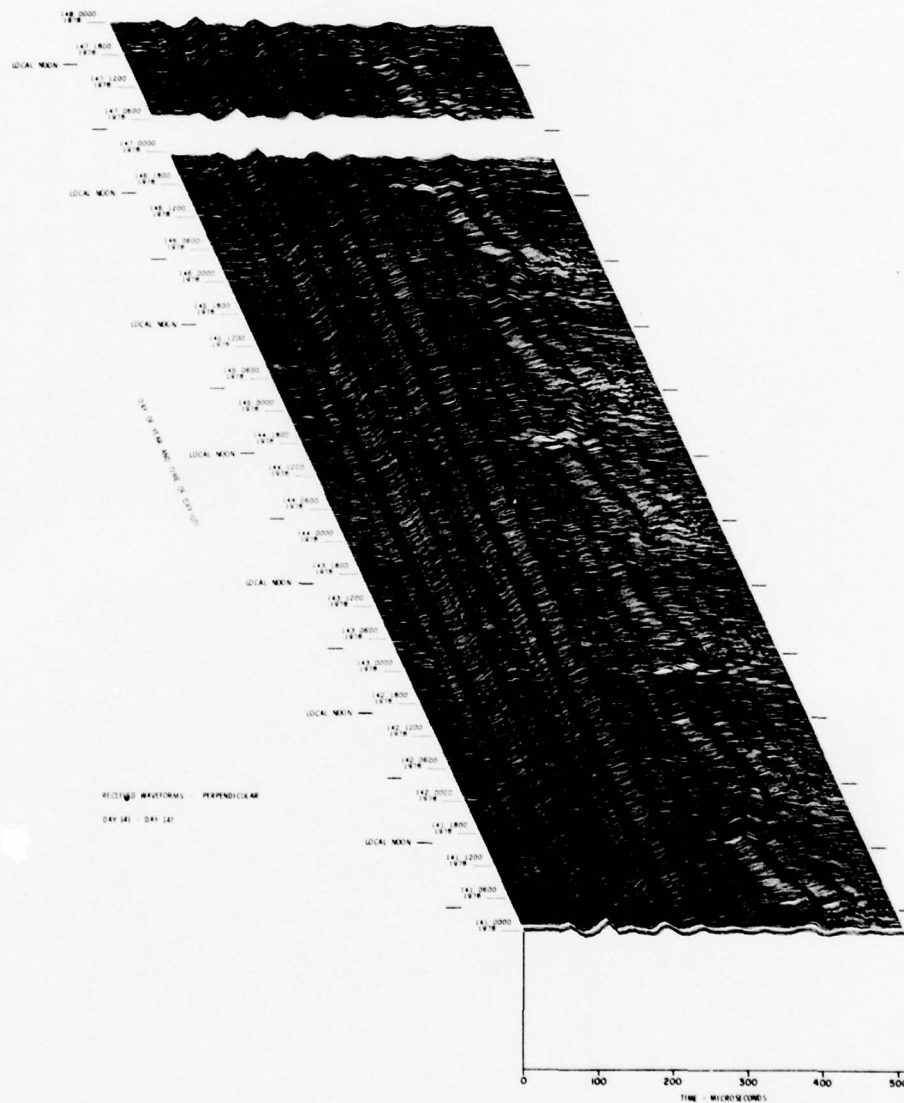


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 141 (21 May) - DAY 147 (27 May) 1978 (Cont)
Part S. \perp Waveform Display

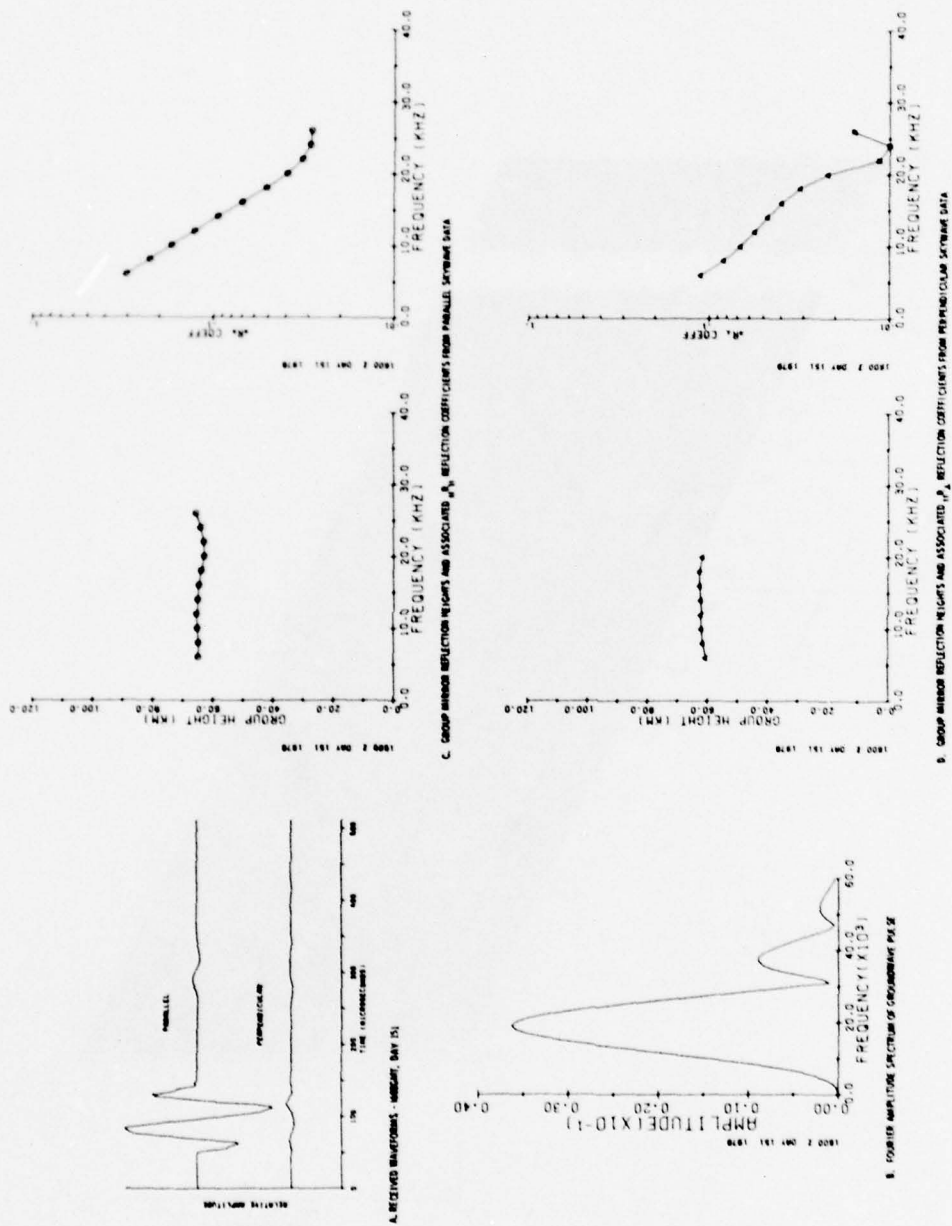


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 148 (28 May) - DAY 154 (3 Jun) 1978

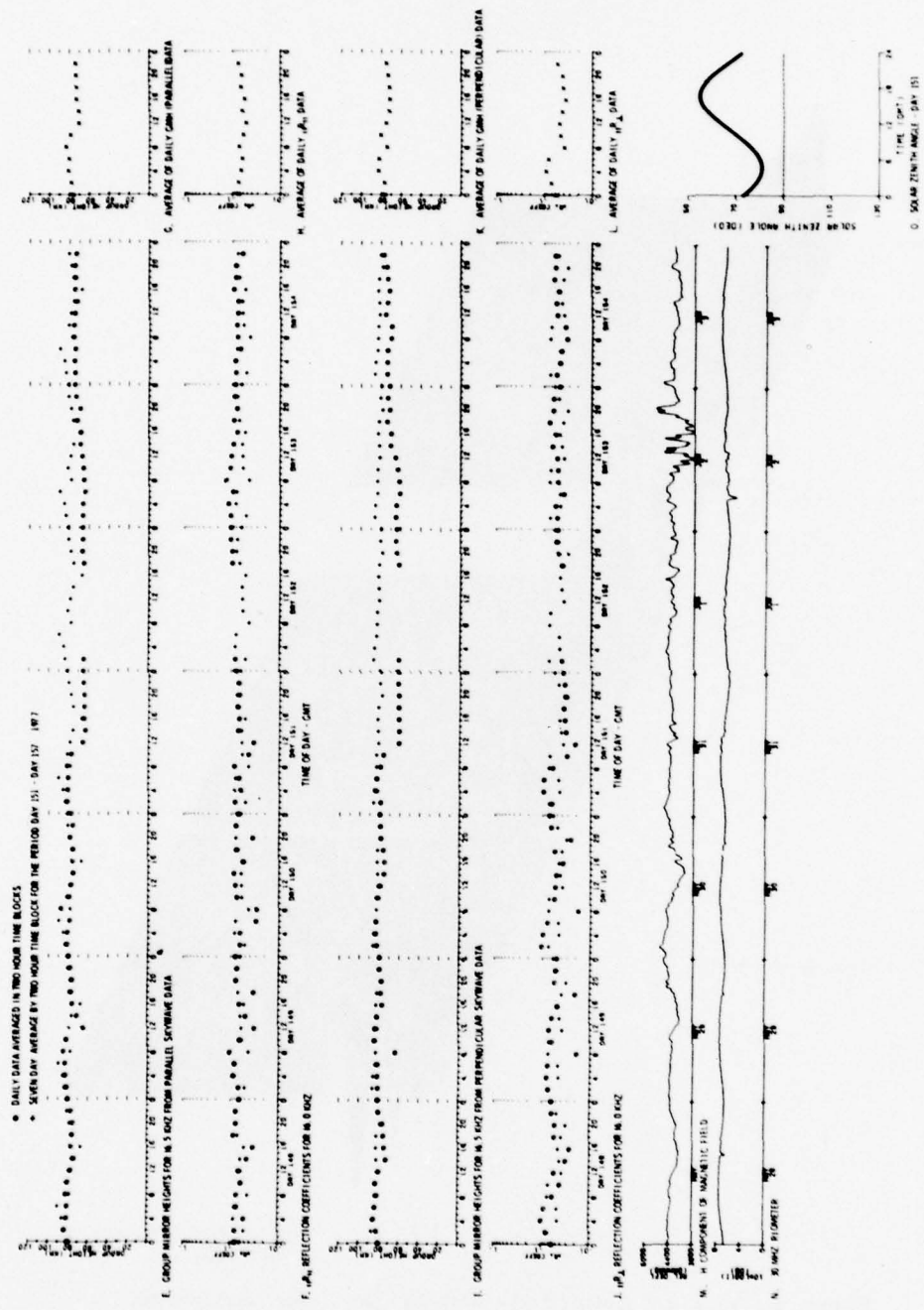
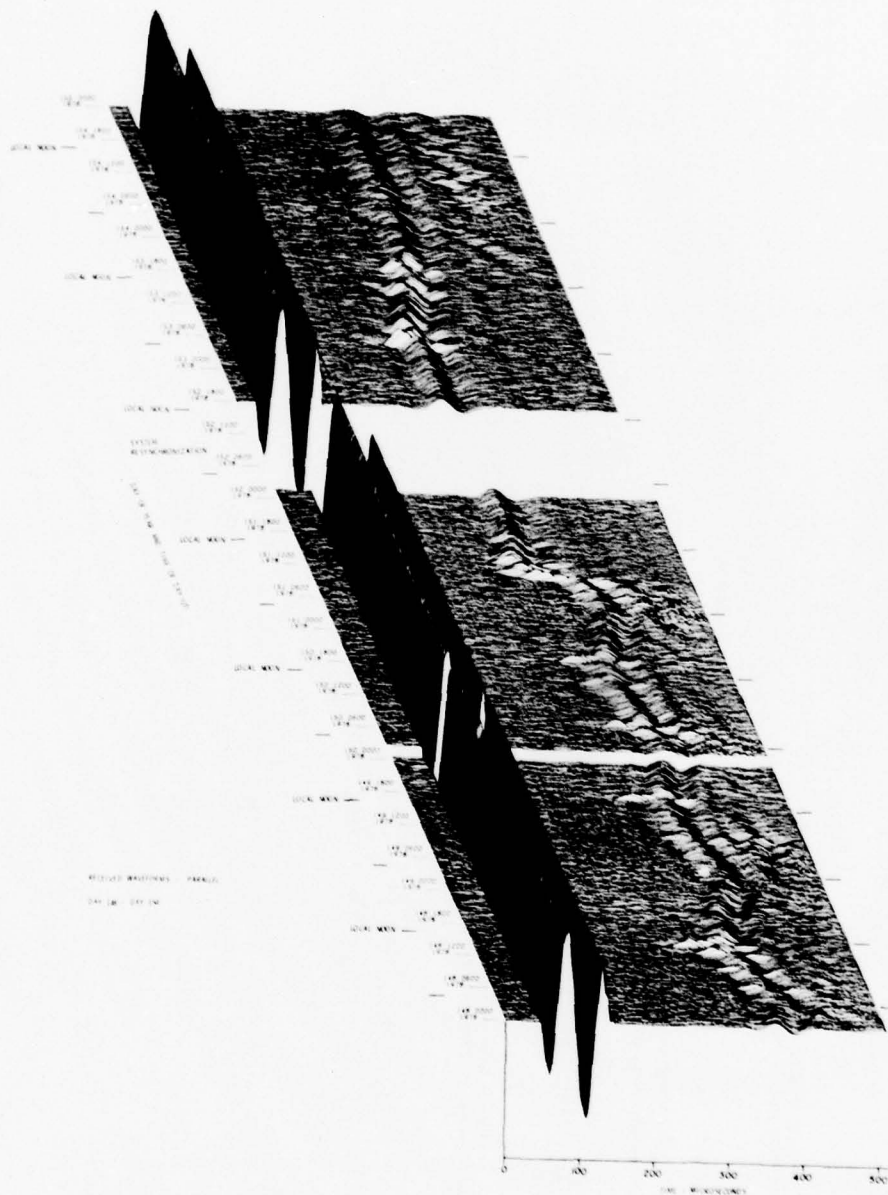


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 148 (28 May) - DAY 154 (3 Jun) 1978 (Cont)



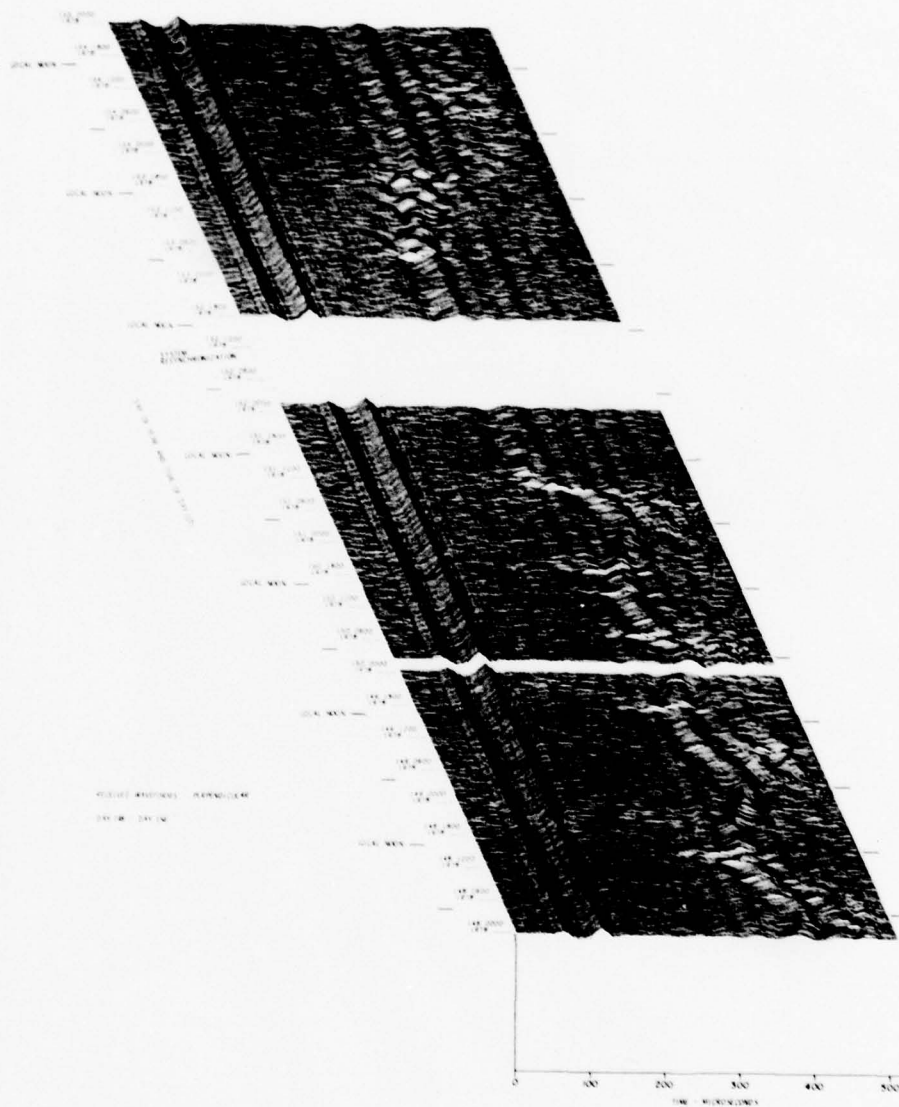


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 148 (28 May) - DAY 154 (3 Jun) 1978 (Cont)
 Part S. L Waveform Display

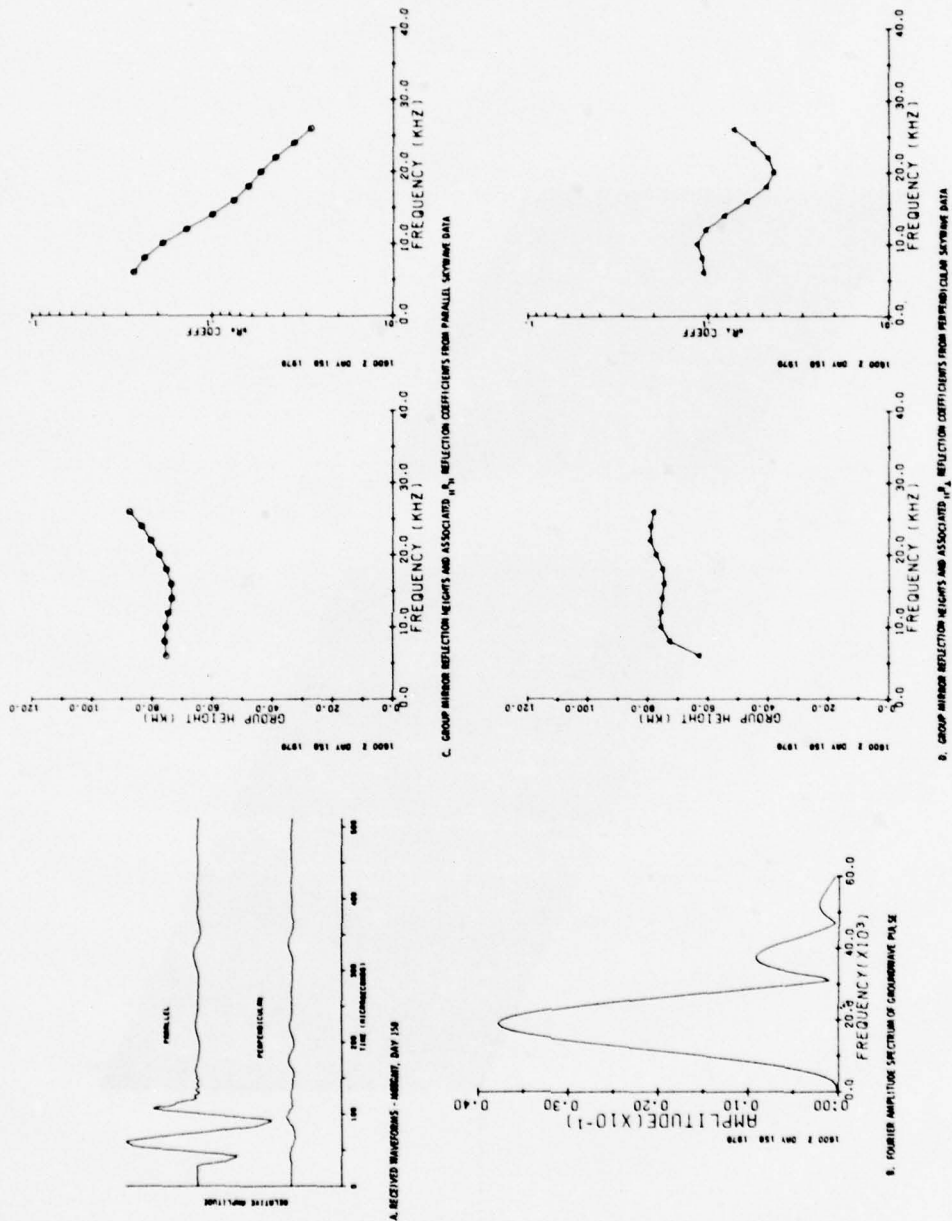


Figure 9. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 155 (4 Jun) - DAY 161 (10 Jun) 1978

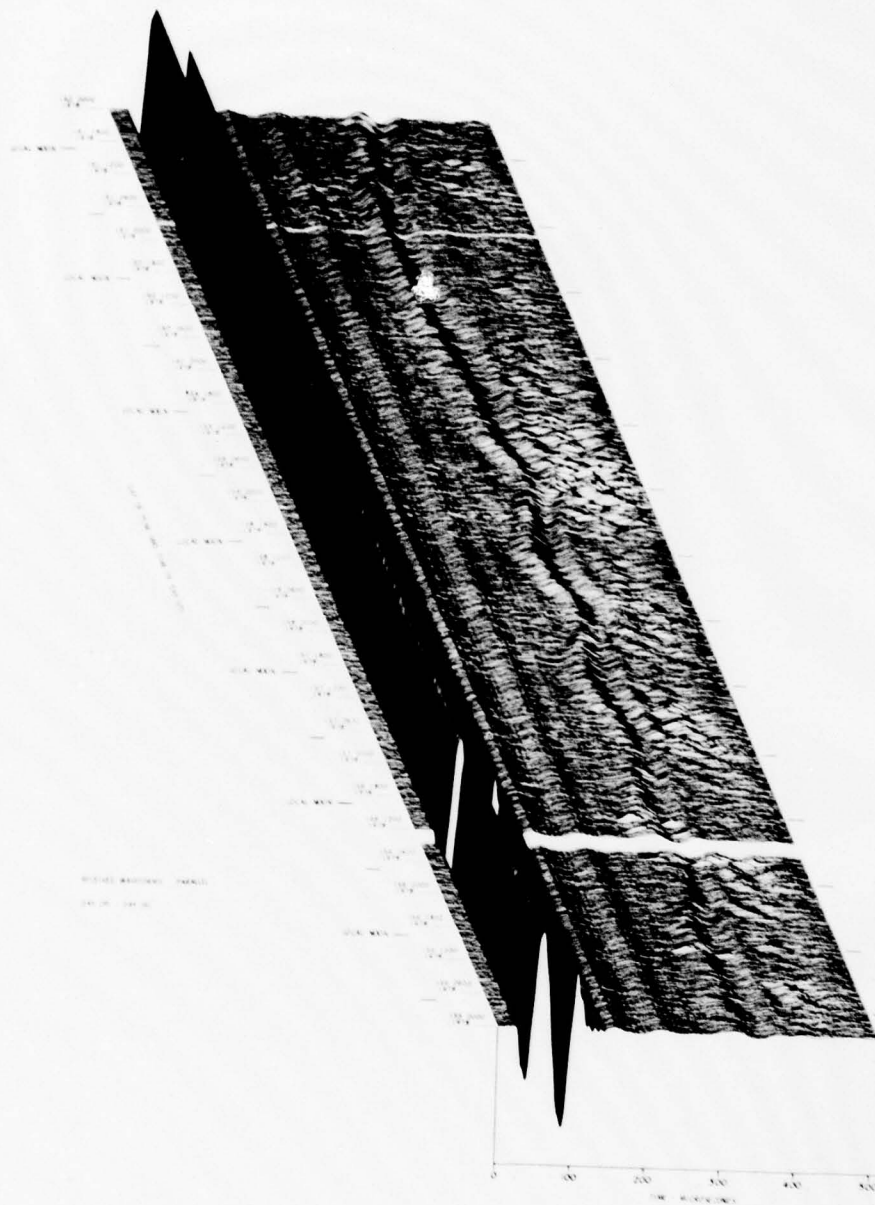


Figure 9. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 155 (4 Jun) - DAY 161 (10 Jun) 1978 (Cont)
 Part R. II Waveform Display

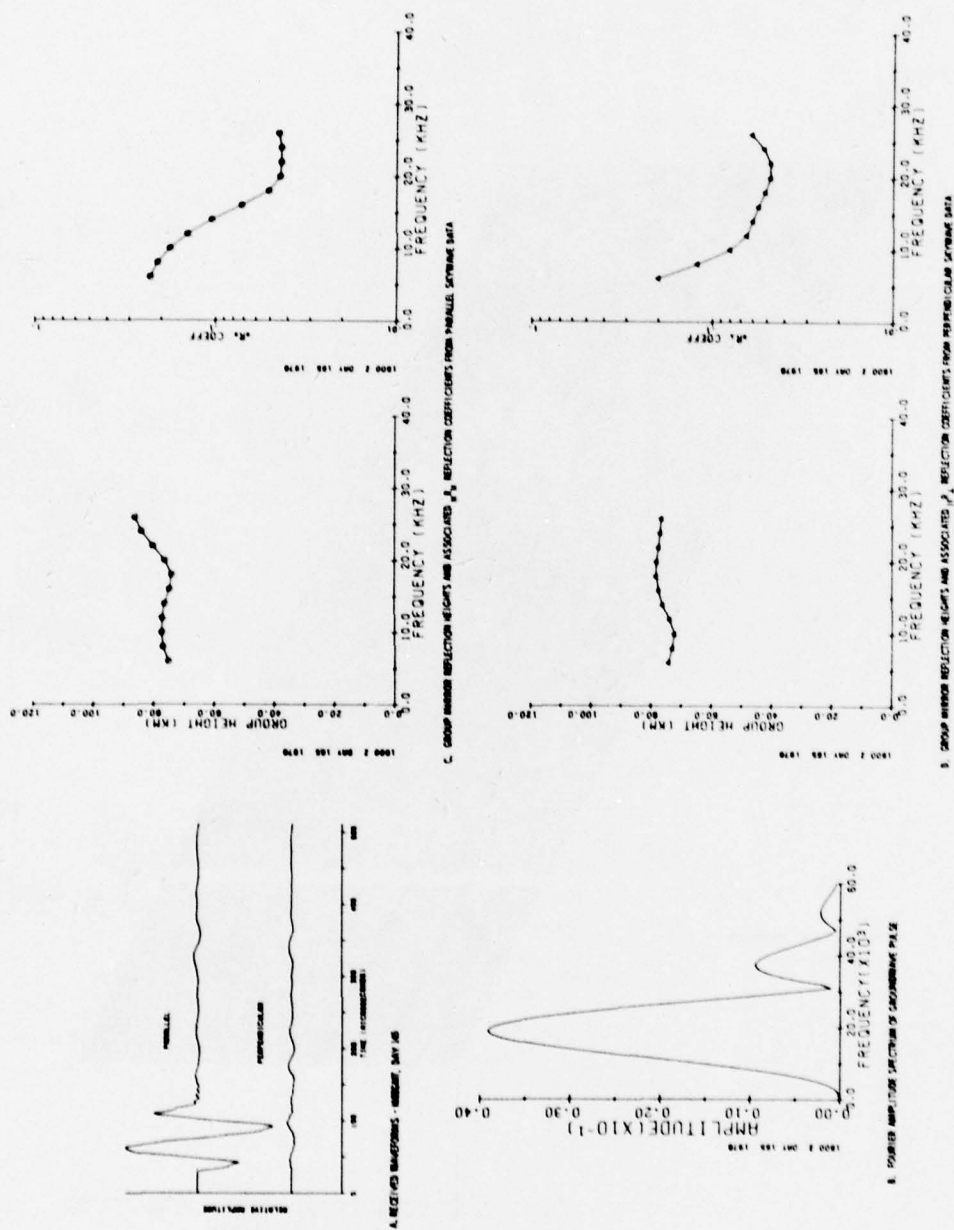


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 162 (11 Jun) - DAY 168 (17 Jun) 1978

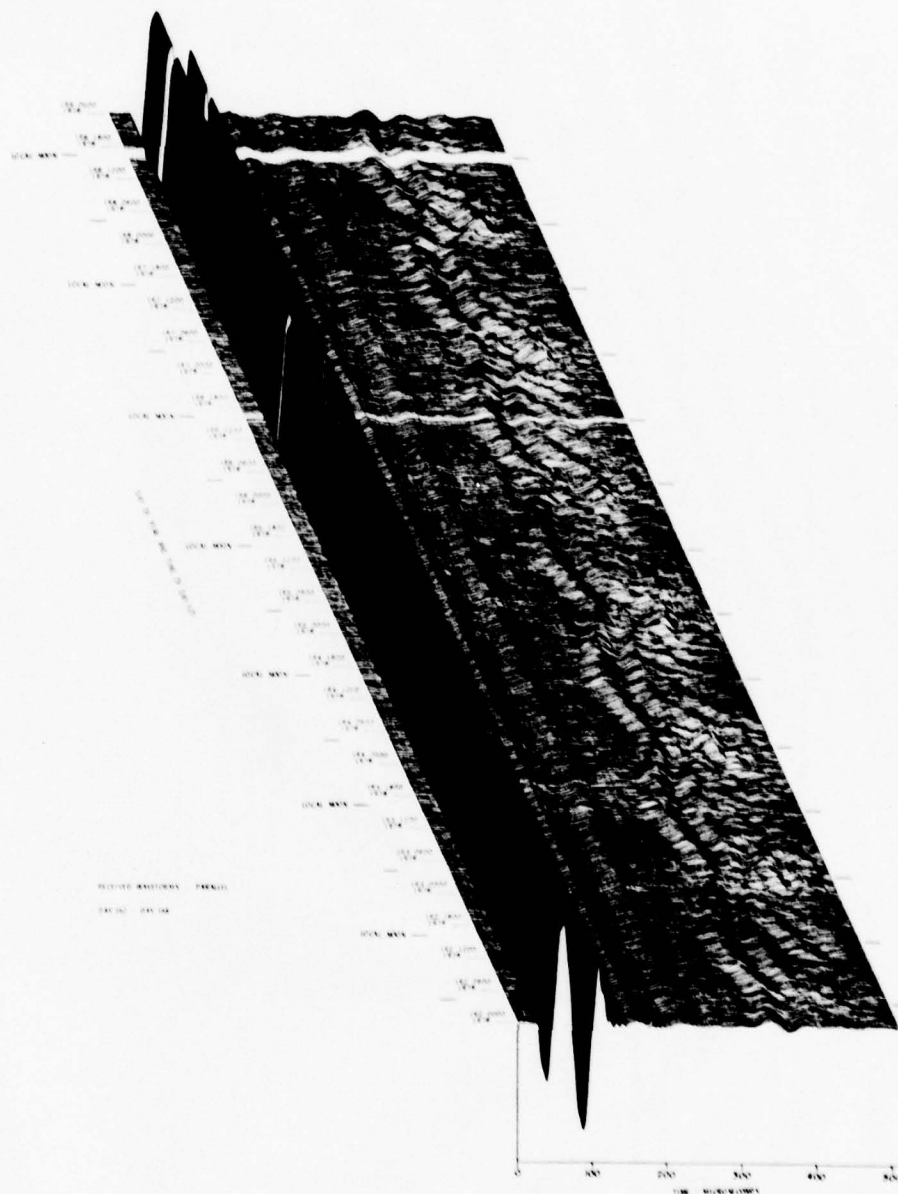


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 162 (11 Jun) - DAY 168 (17 Jun) 1978 (Cont)
 Part R. II Waveform Display

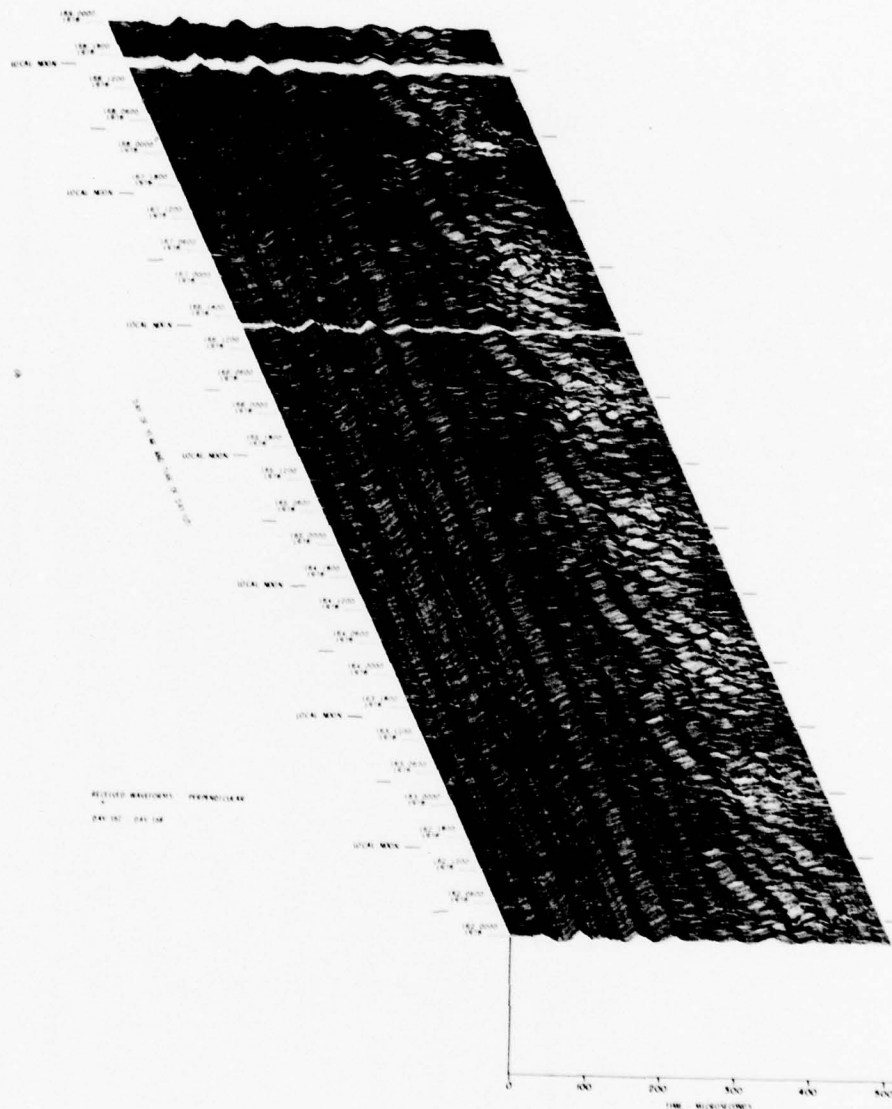


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 162 (11 Jun) - DAY 168 (17 Jun) 1978 (Cont)
 Part S. \perp Waveform Display

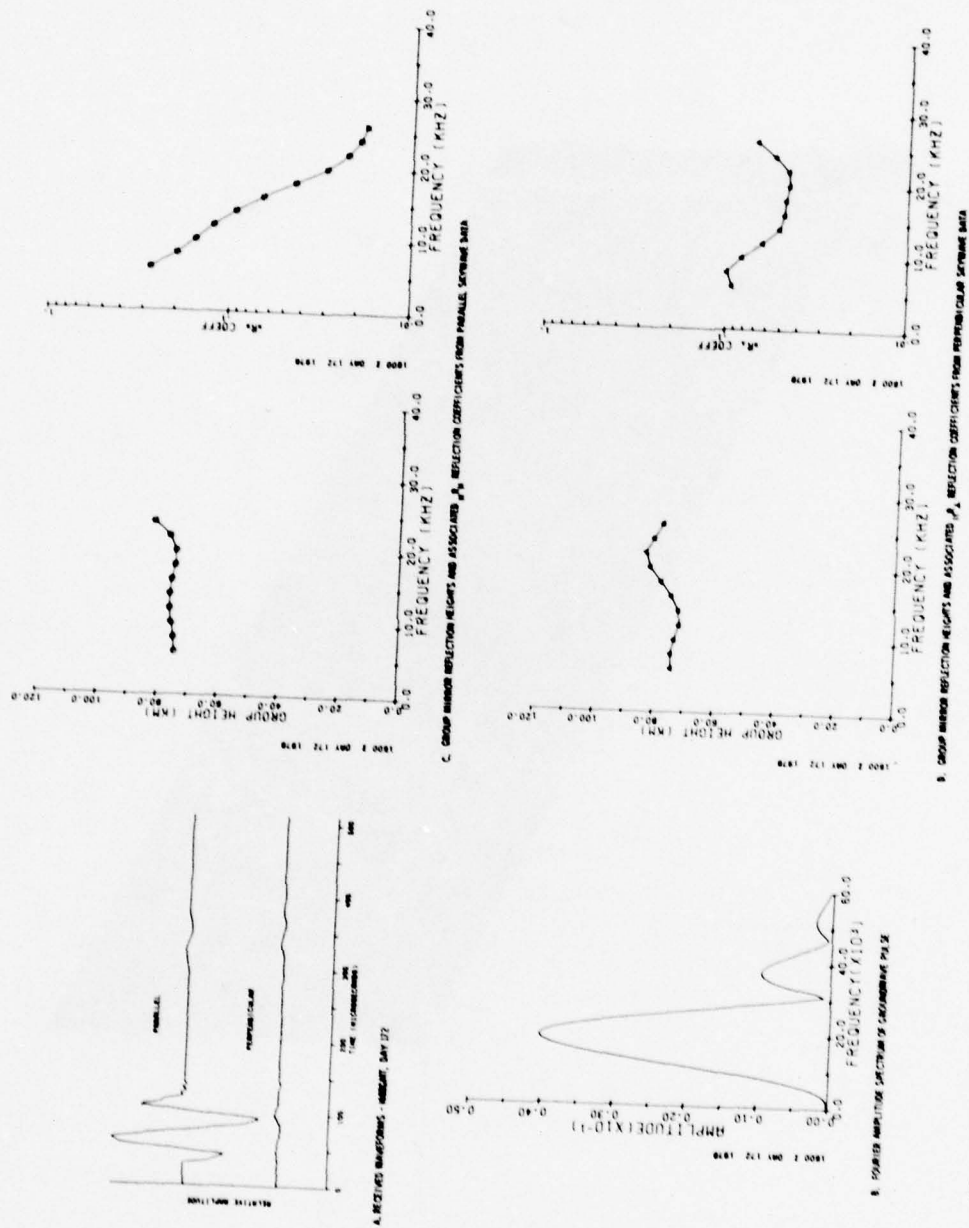


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 169 (18 Jun) - DAY 175 (24 Jun) 1978

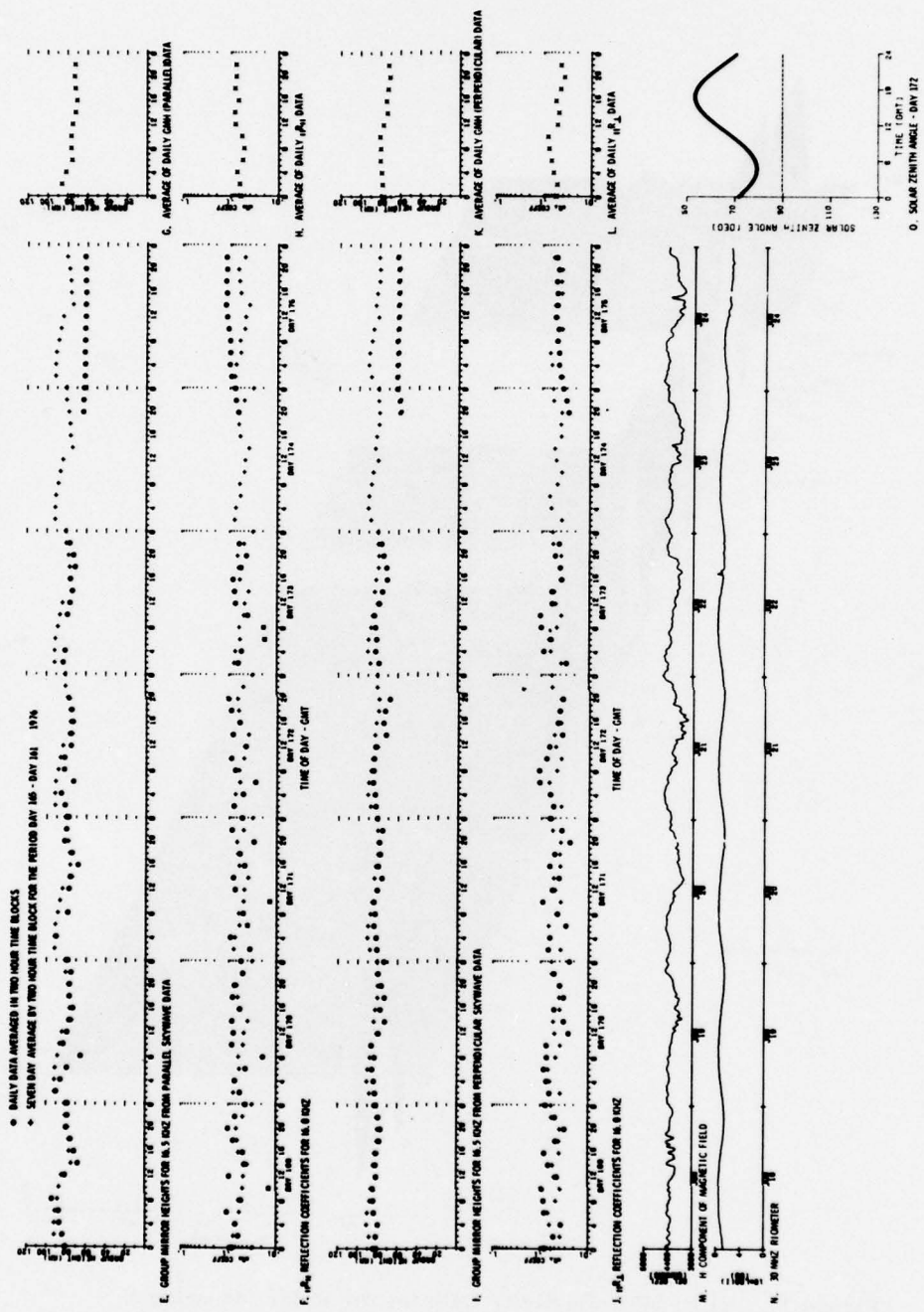


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 169 (18 Jun) - DAY 175 (24 Jun) 1978 (Cont)

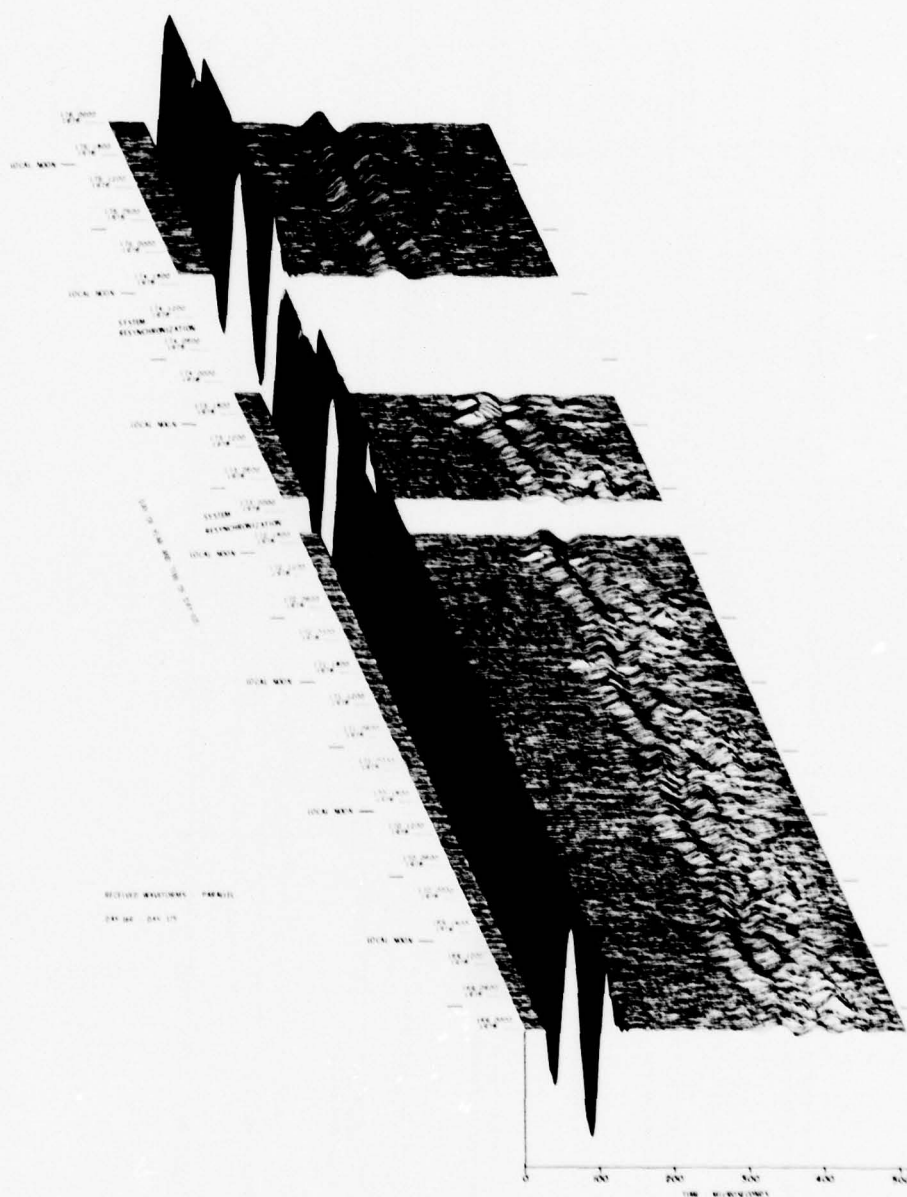


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 169 (18 Jun) - DAY 175 (24 Jun) 1978 (Cont)
 Part R. II Waveform Display

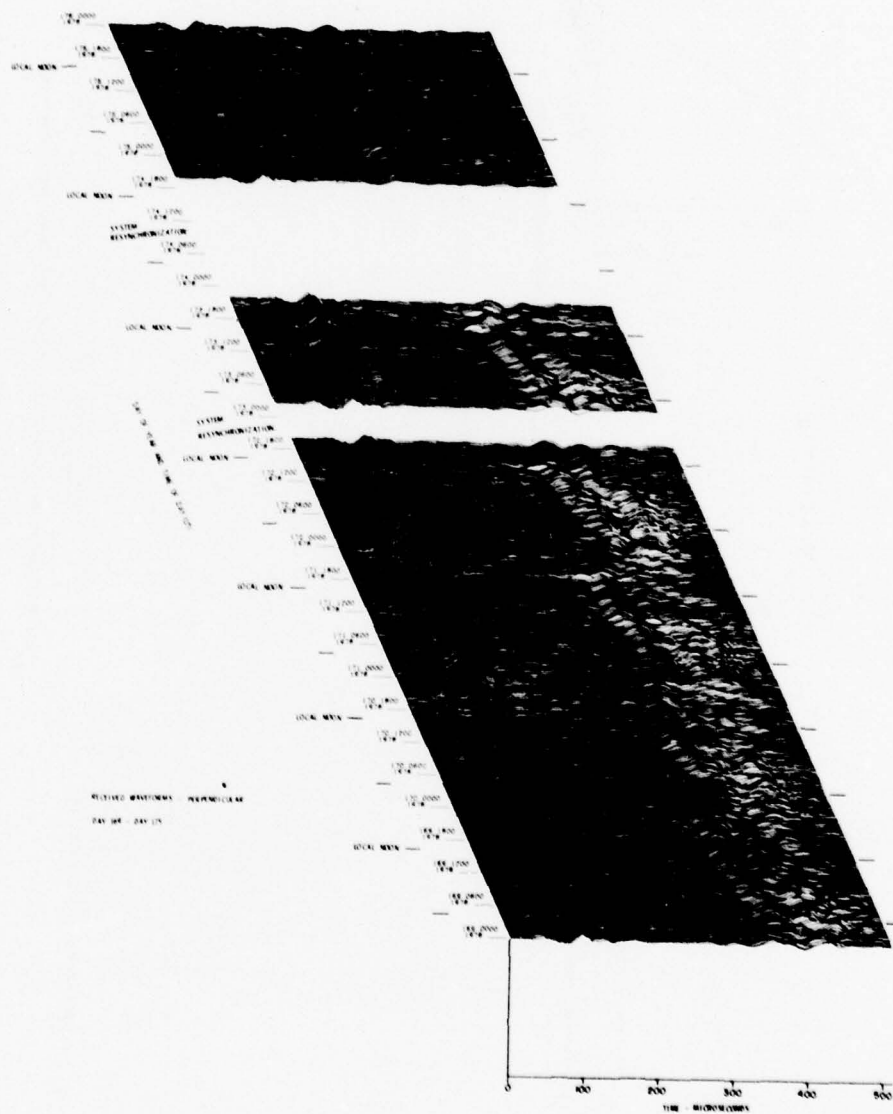


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 169 (18 Jun) - DAY 175 (24 Jun) 1978 (Cont)
 Part S. \perp Waveform Display

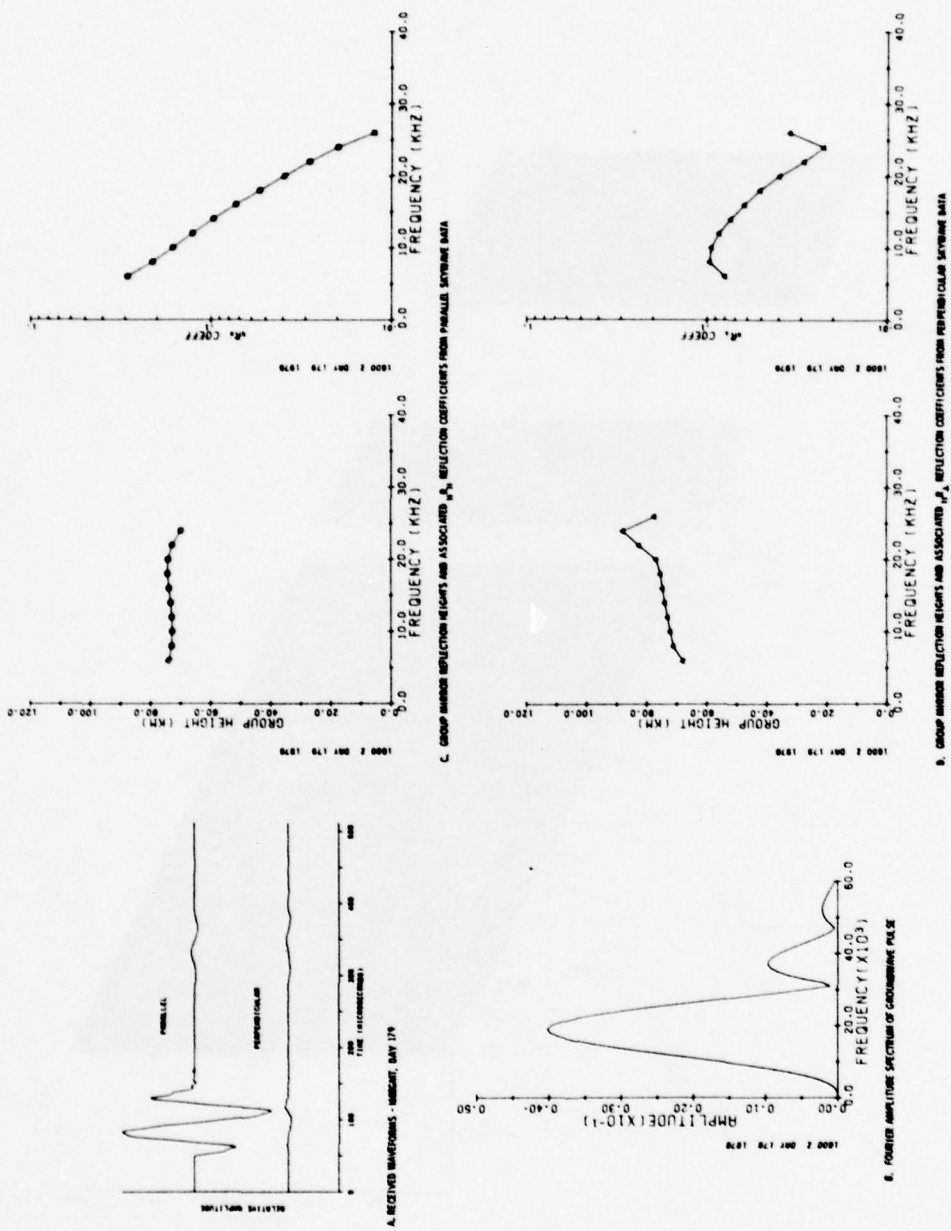


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 176 (25 Jun) - DAY 182 (1 Jul) 1978

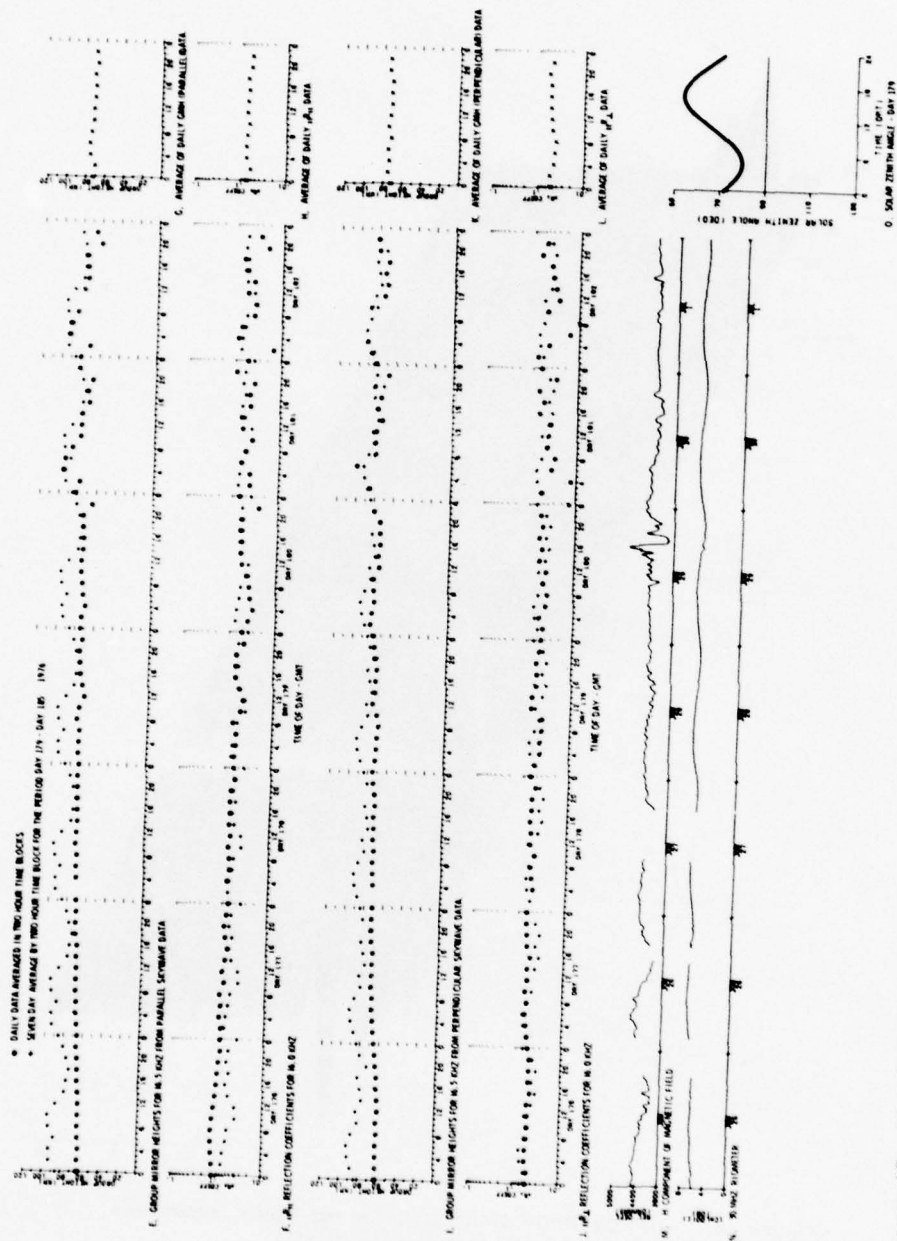


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 176 (25 Jun) - DAY 182 (1 Jul) 1978 (Cont)

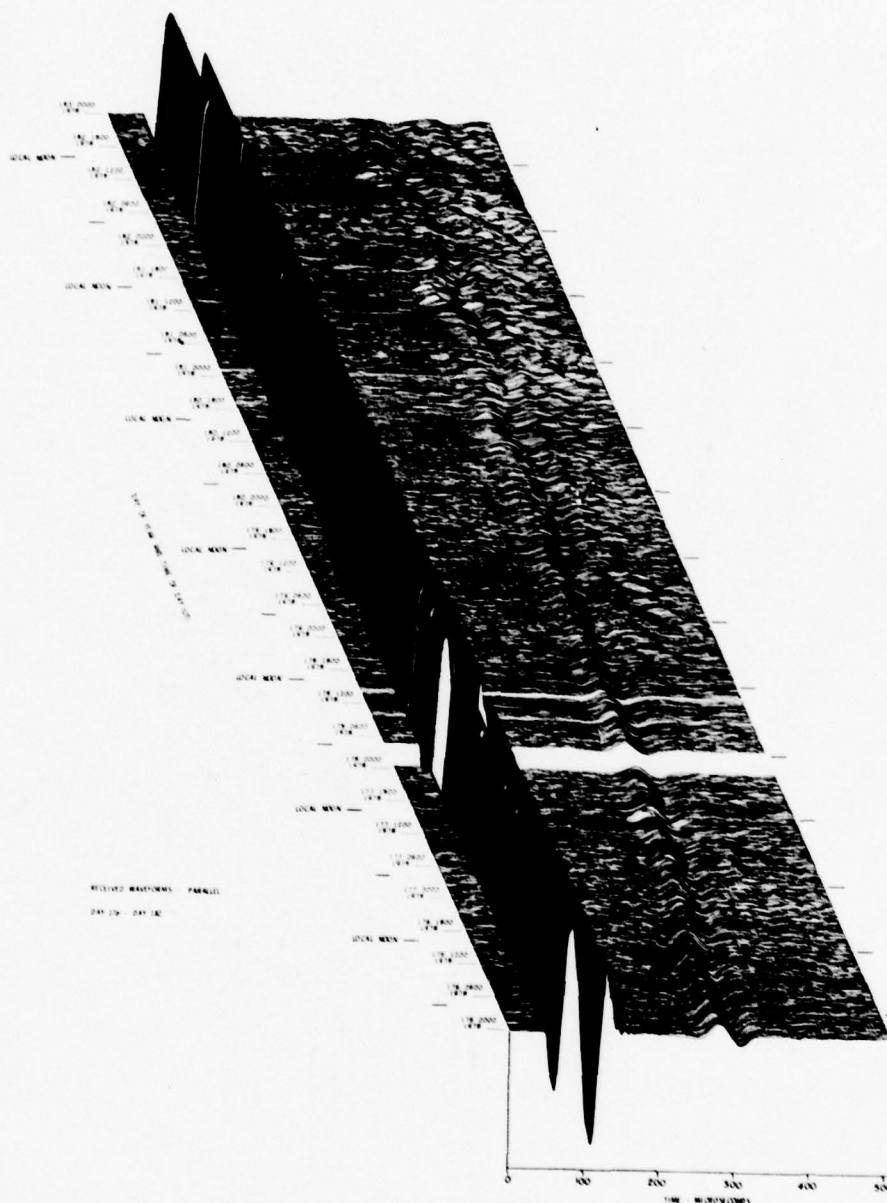


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 176 (25 Jun) - DAY 182 (1 Jul) 1978 (Cont)
 Part R. || Waveform Display

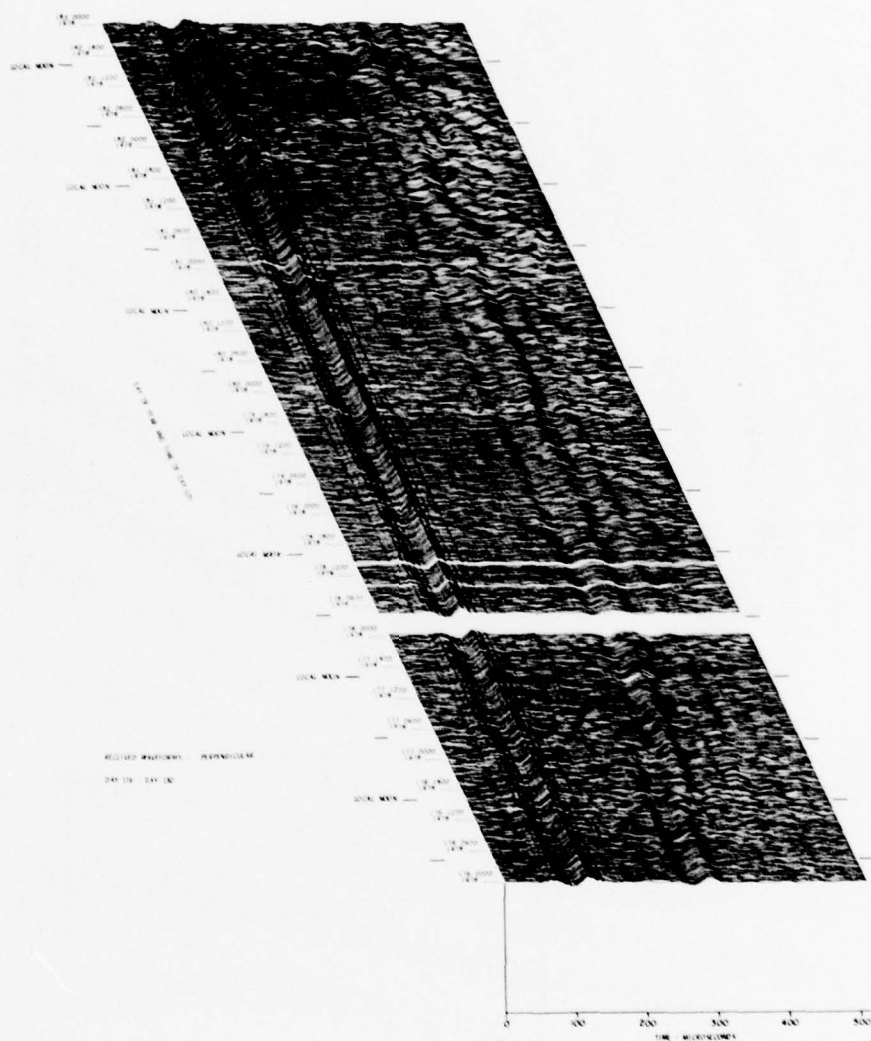


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 176 (25 Jun) - DAY 182 (1 Jul) 1978 (Cont)
 Part S. \perp Waveform Display

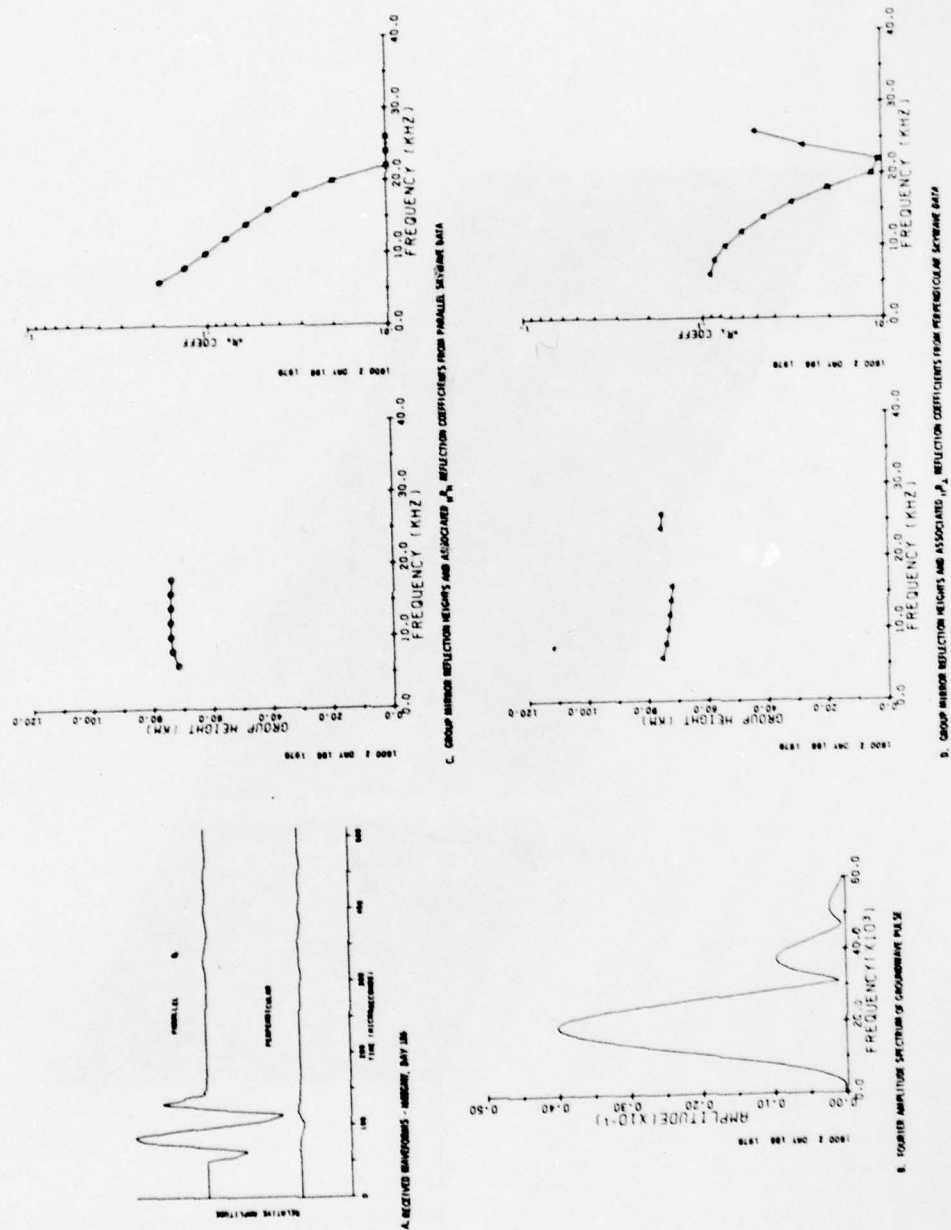


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 183 (2 Jul) - DAY 189 (8 Jul) 1978

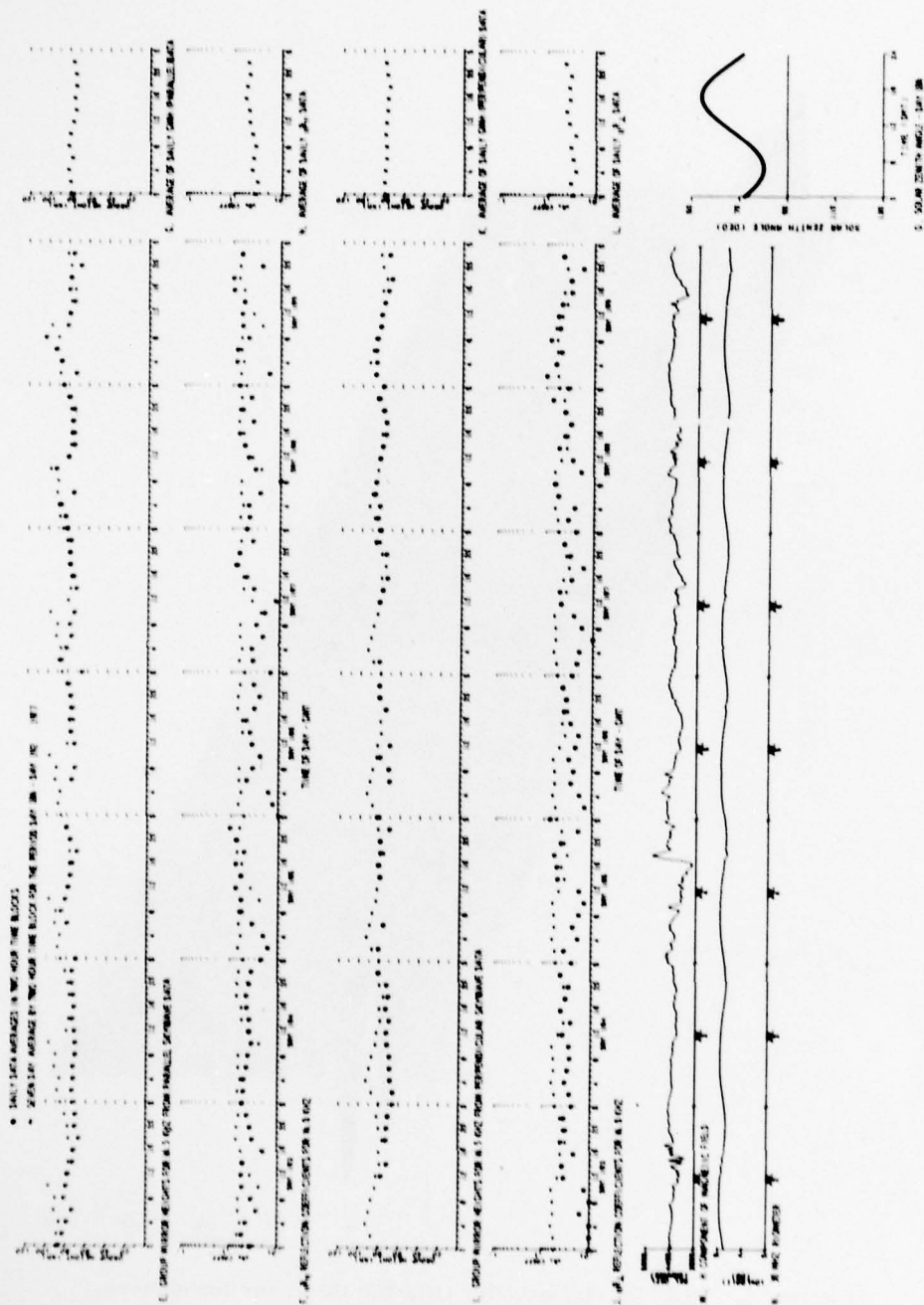


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 183 (2 Jul) - DAY 189 (8 Jul) 1978 (Cont)

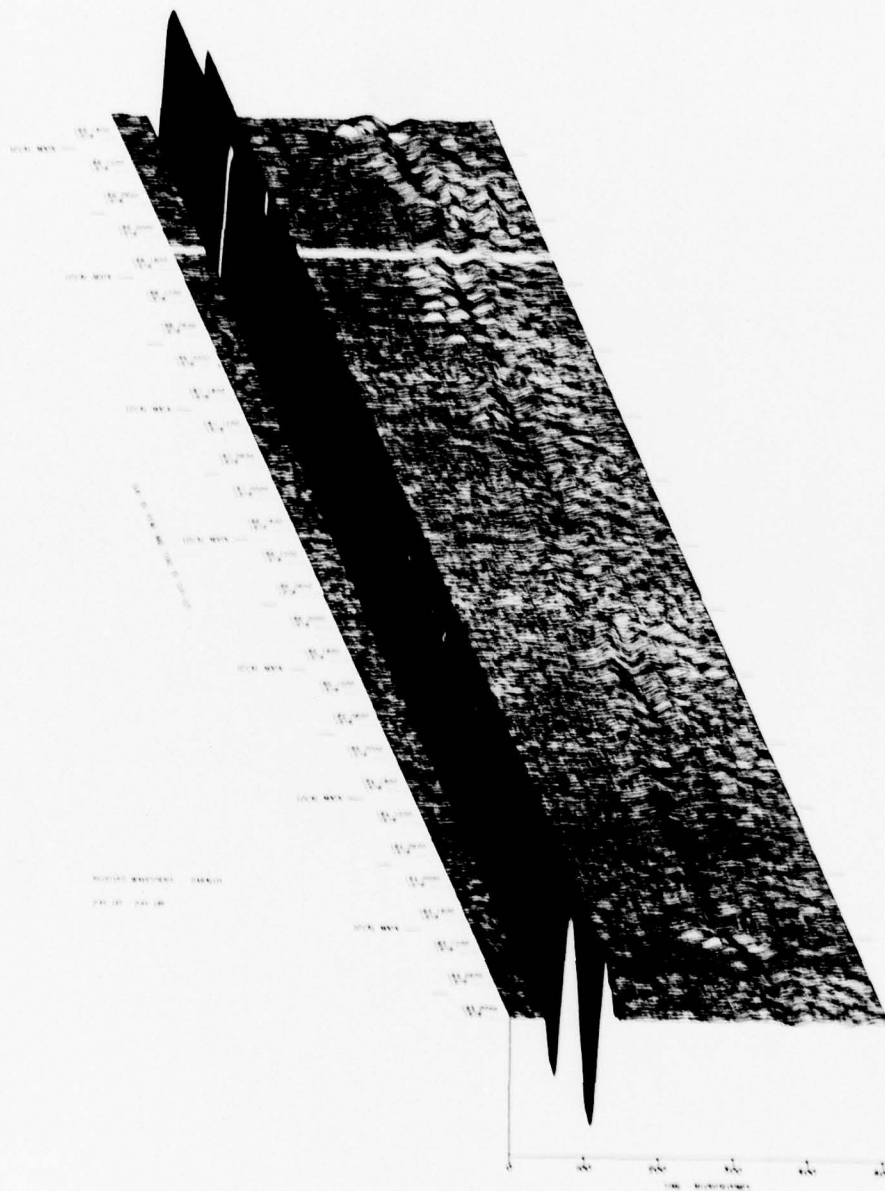


Figure 13. VLF/1F Reflectivity Data for the Polar Ionosphere,
 DAY 183 (2 Jul) - DAY 189 (8 Jul) 1978 (Cont)
 Part R. II Waveform Display

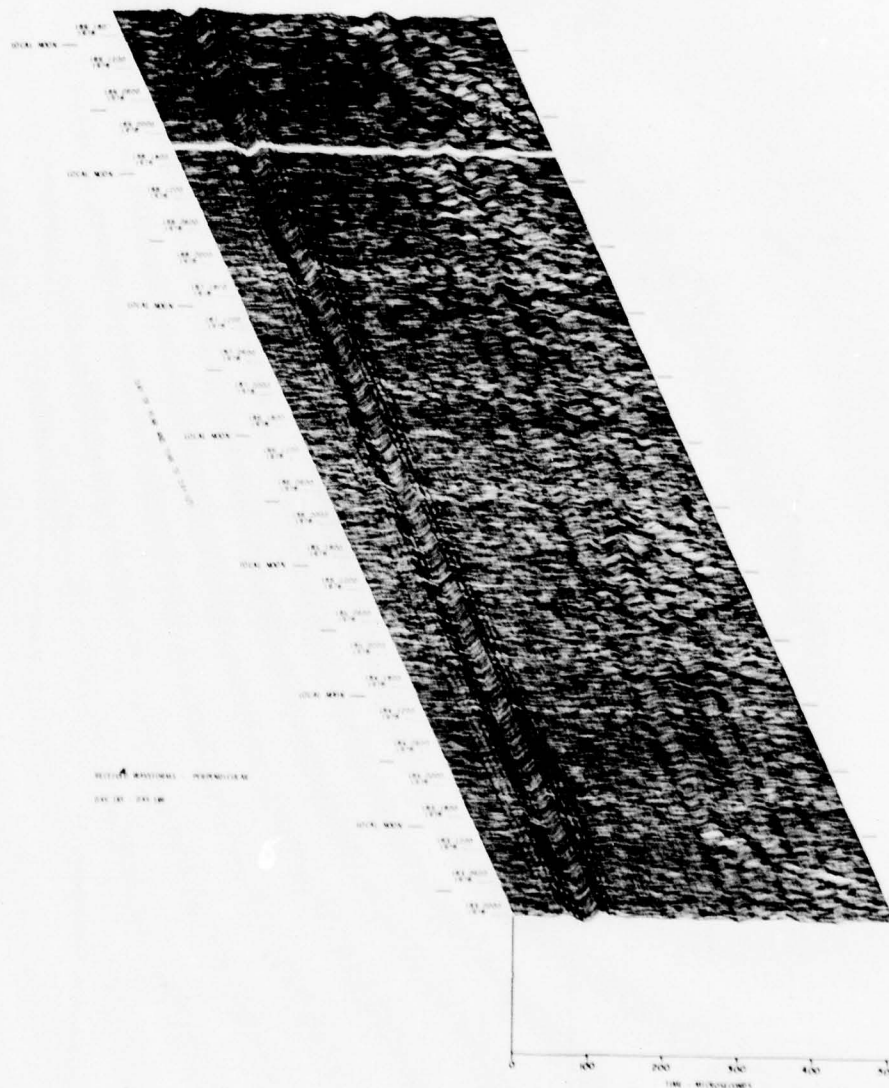


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 183 (2 Jul) - DAY 189 (8 Jul) 1978 (Cont)
 Part S. \perp Waveform Display

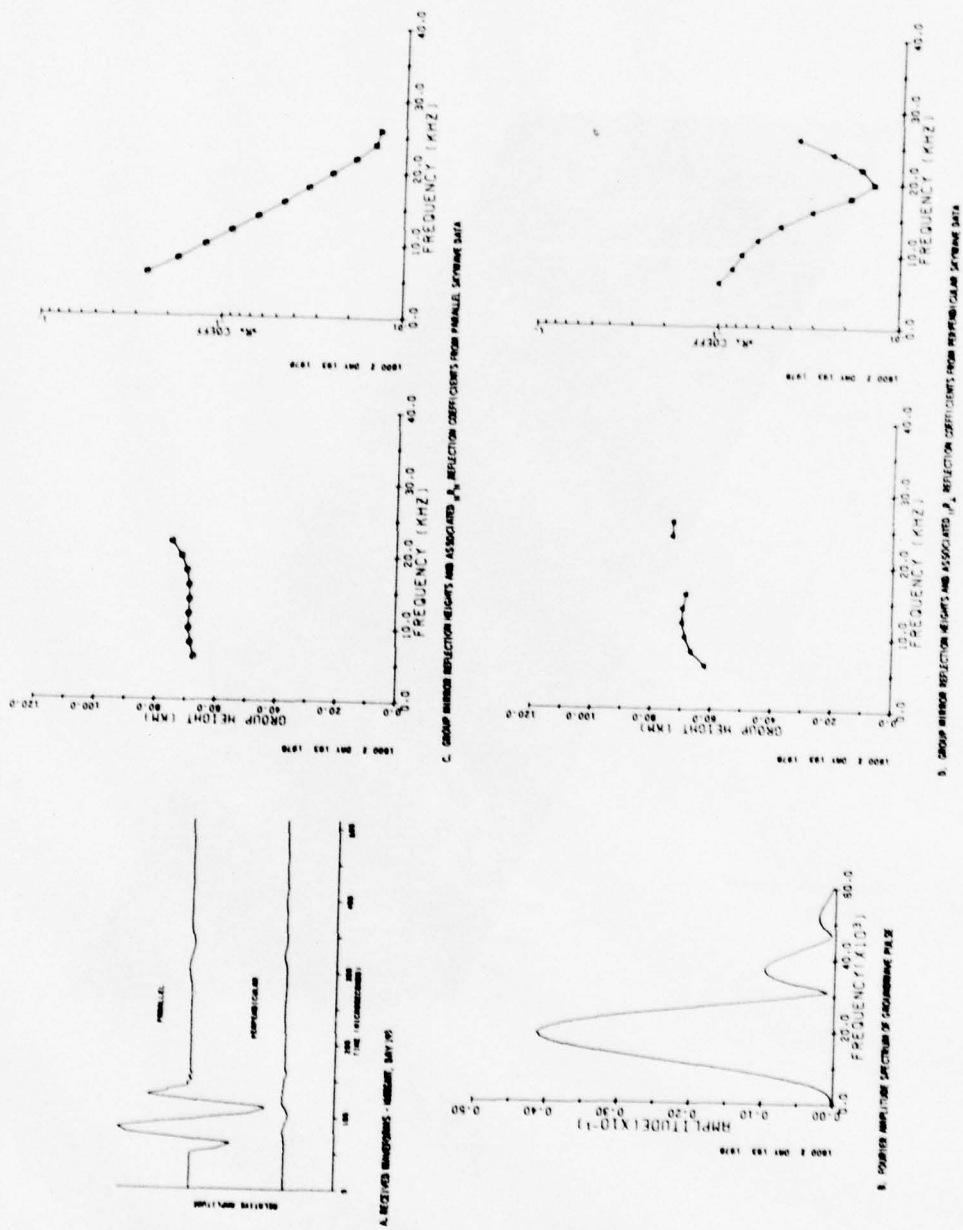


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 190 (9 Jul) - DAY 196 (15 Jul) 1978

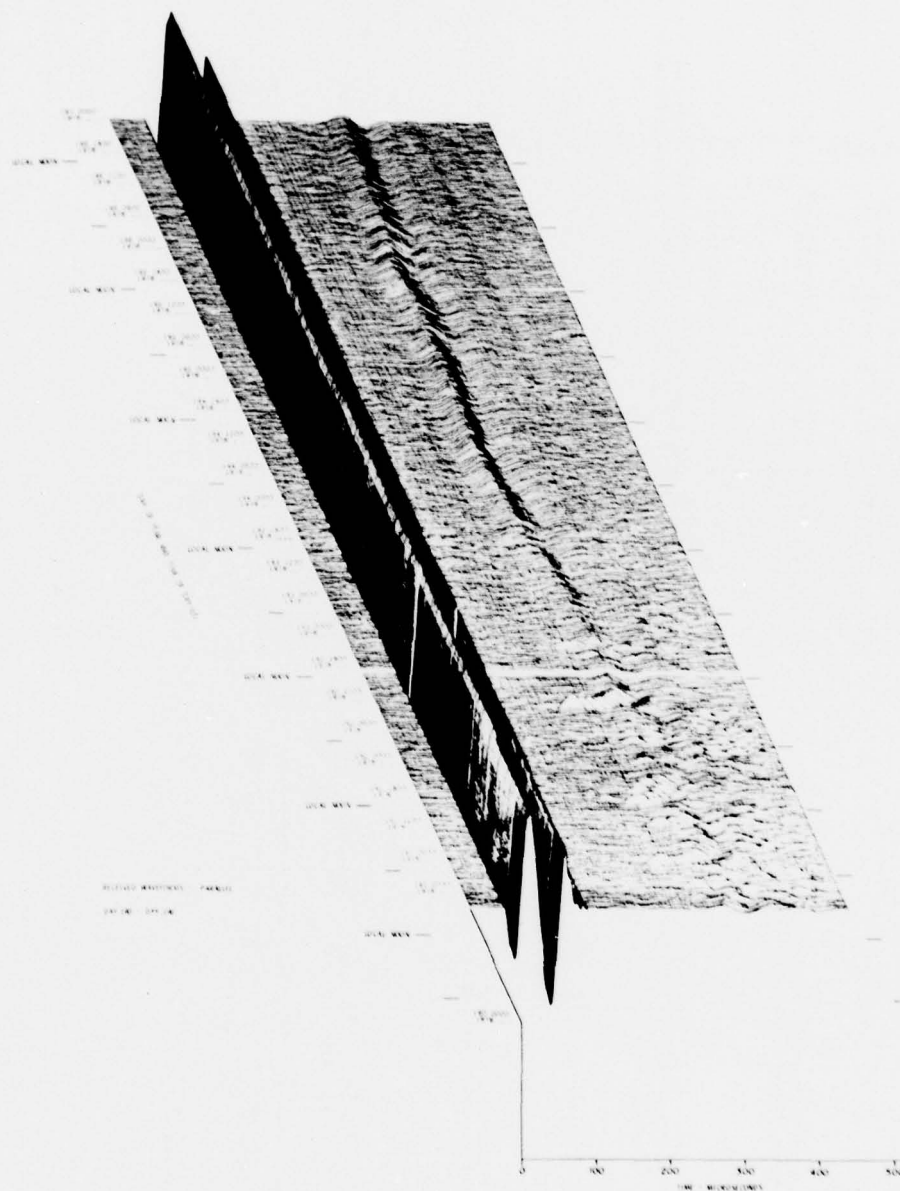


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 190 (9 Jul) – DAY 196 (15 Jul) 1978 (Cont)
 Part R. II Waveform Display

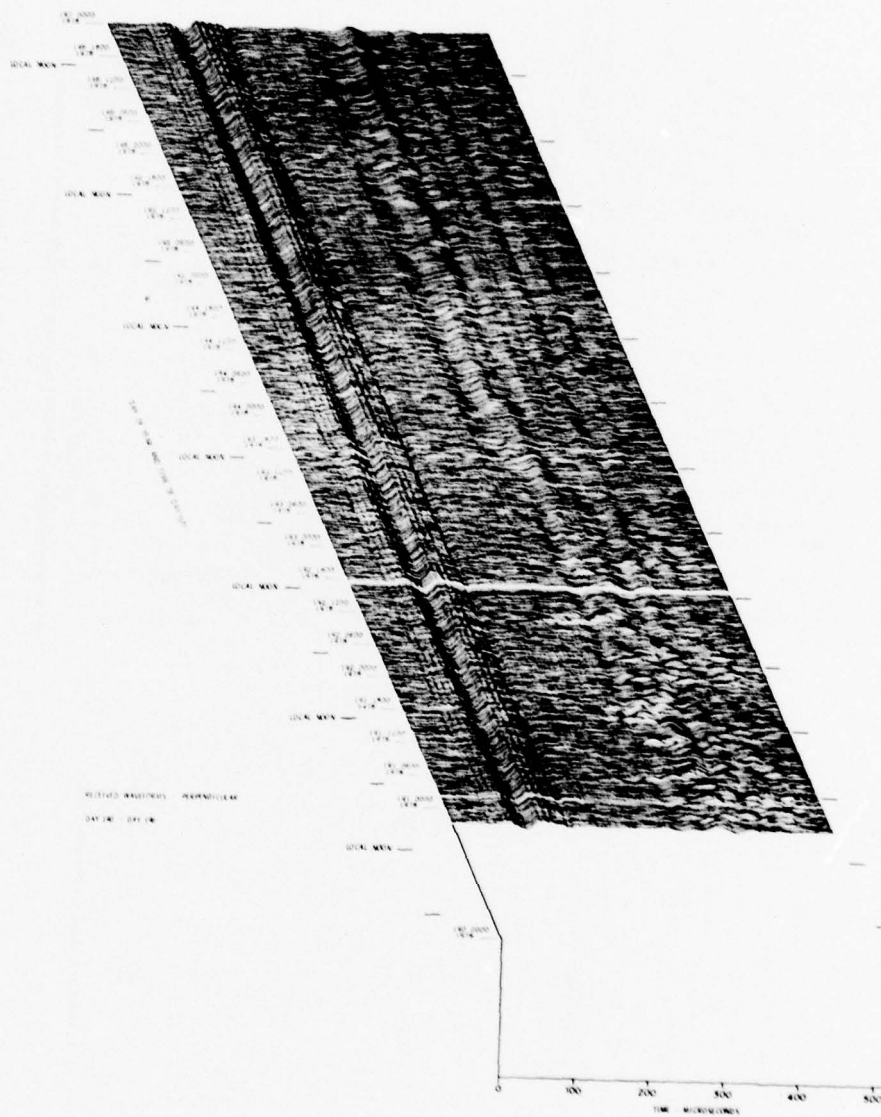


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 190 (9 Jul) - DAY 196 (15 Jul) 1978 (Cont)
 Part S. \perp Waveform Display

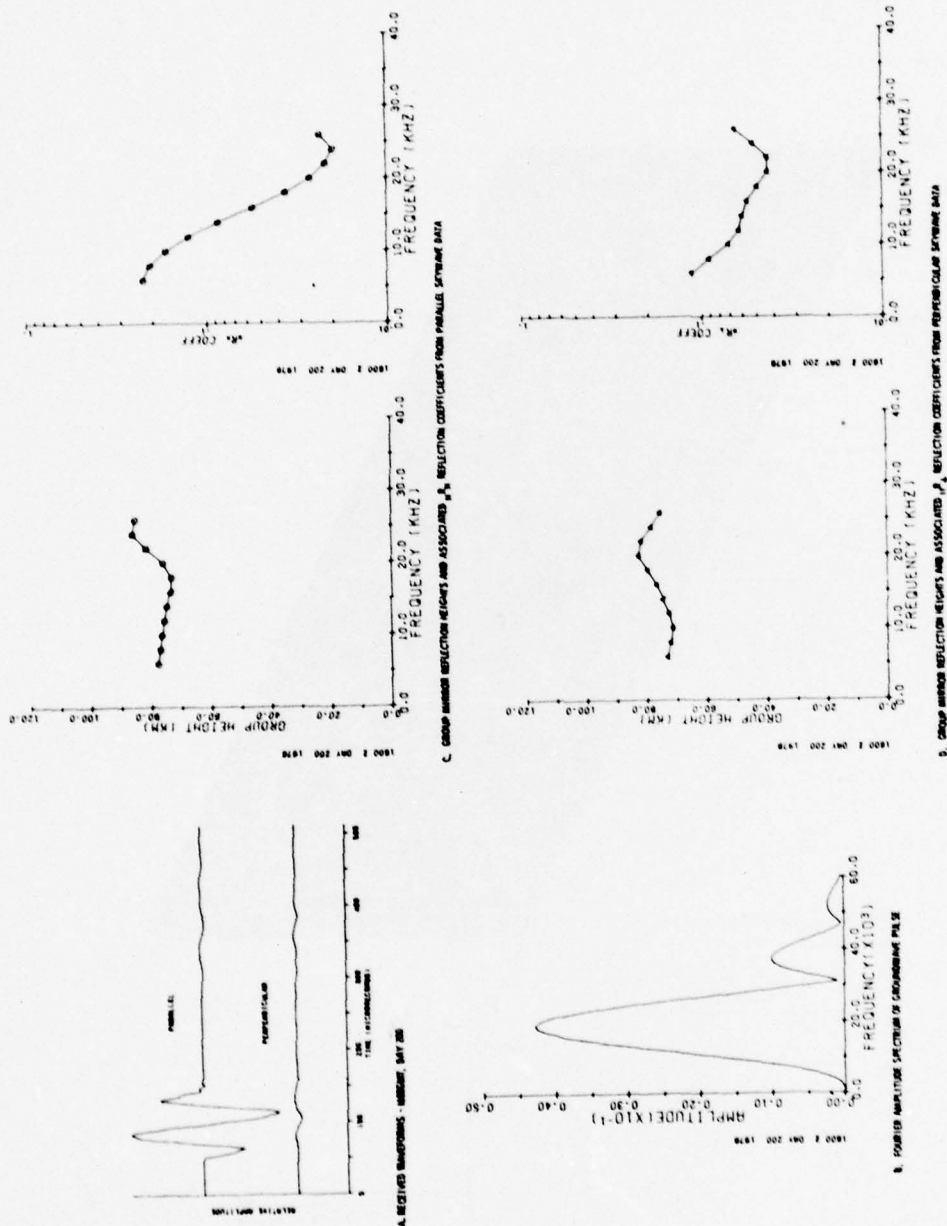


Figure 15. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 197 (16 Jul) - DAY 203 (22 Jul) 1978

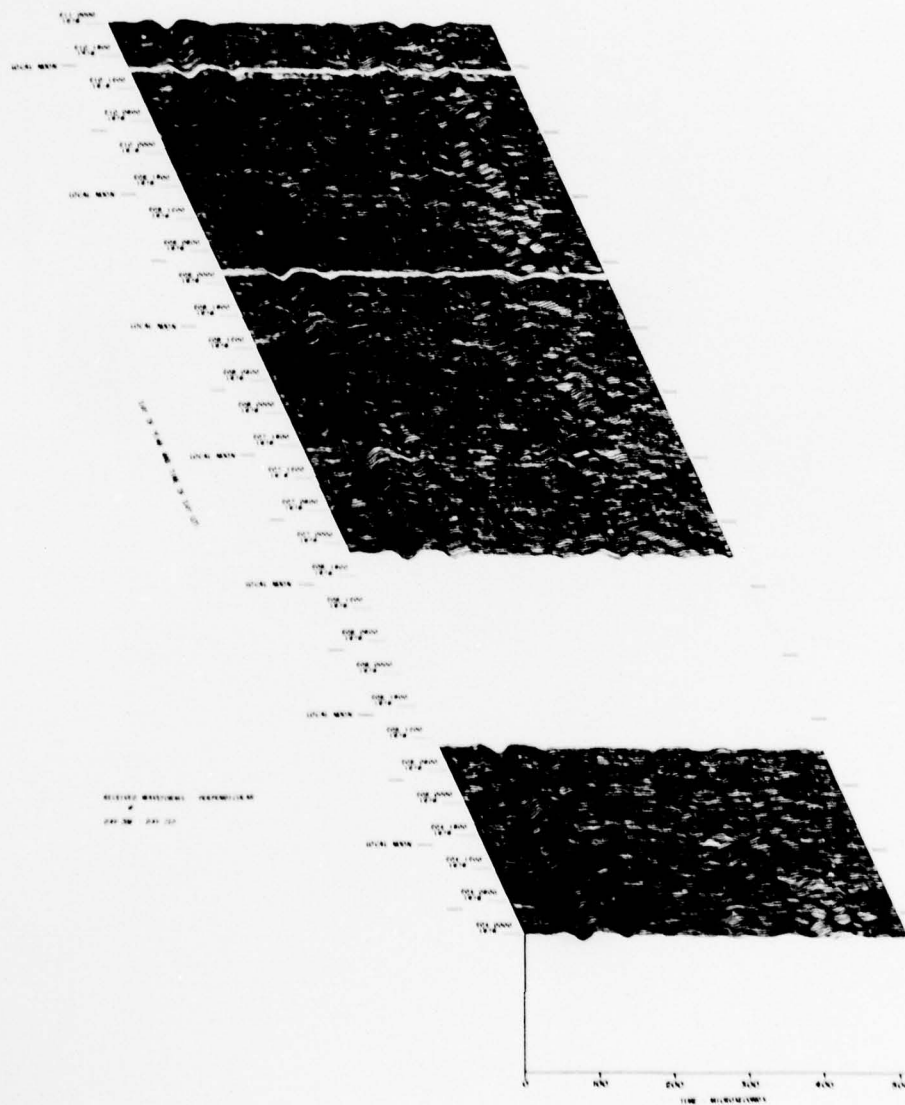


Figure 16. VLF/LE Reflectivity Data for the Polar Ionosphere,
 DAY 204 (23 Jul) - DAY 210 (29 Jul) 1978 (Cont)
 Part S. \perp Waveform Display

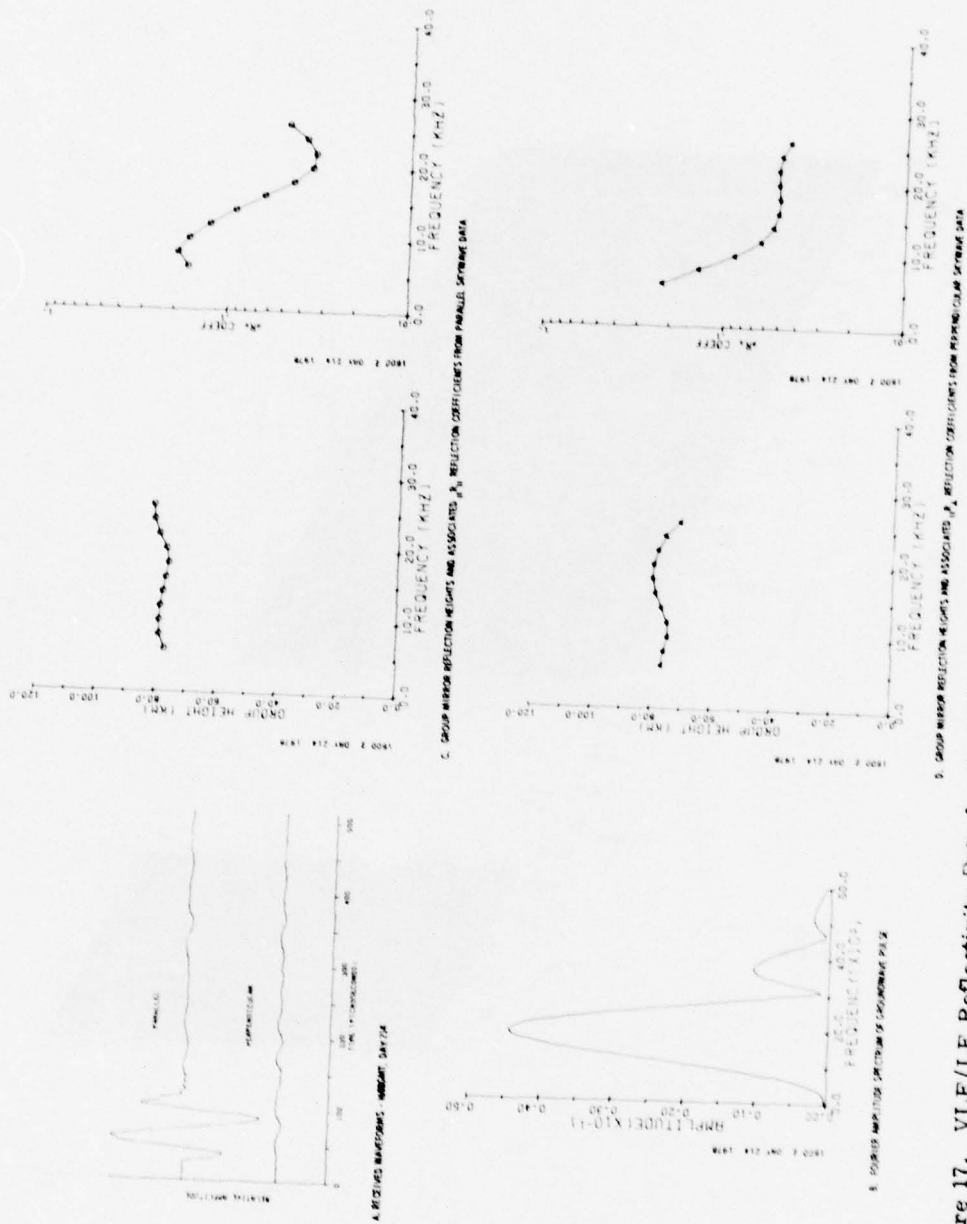


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 211 (30 Jul) - DAY 217 (5 Aug) 1978

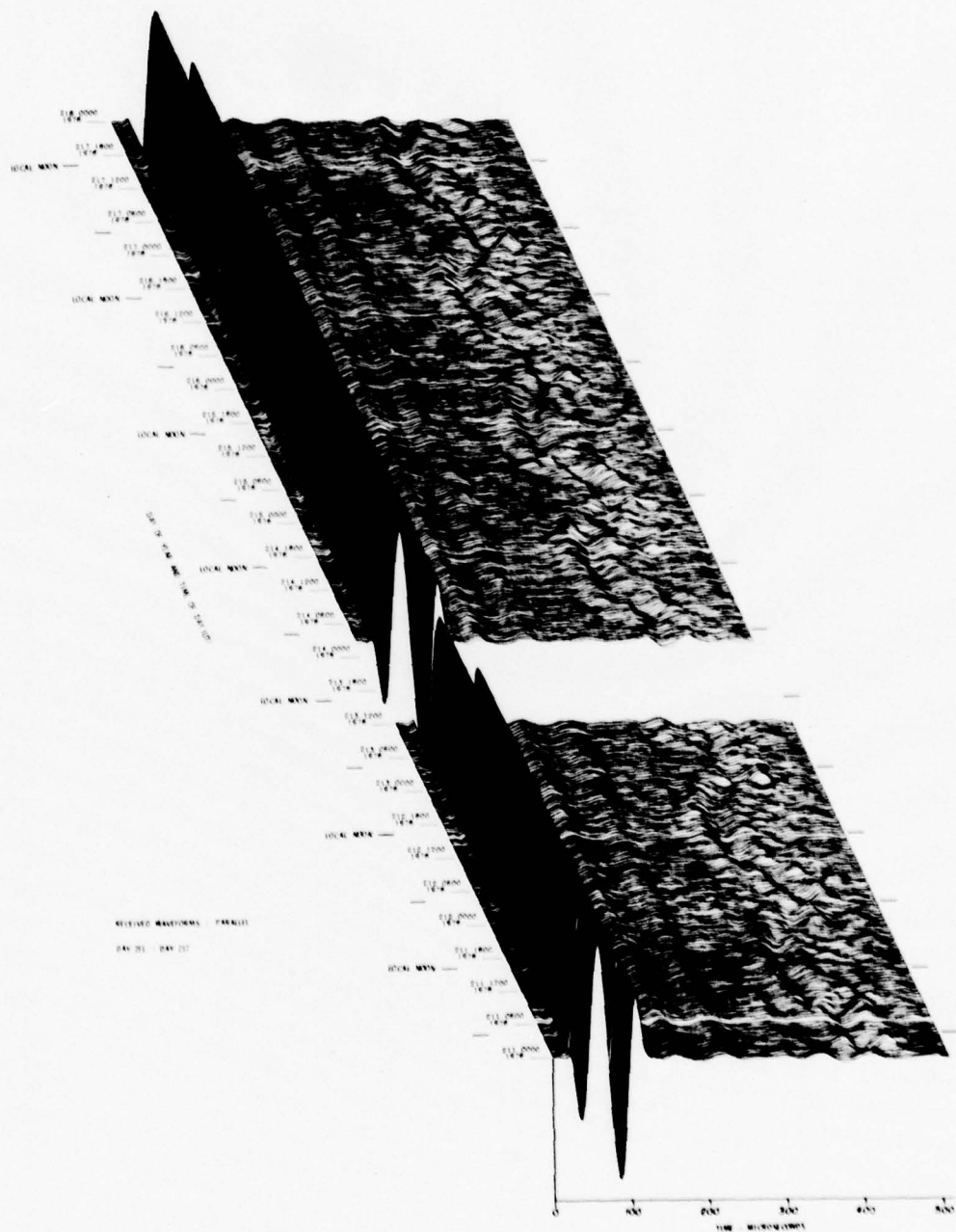


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 211 (30 Jul) - DAY 217 (5 Aug) 1978 (Cont)
 Part R. II Waveform Display

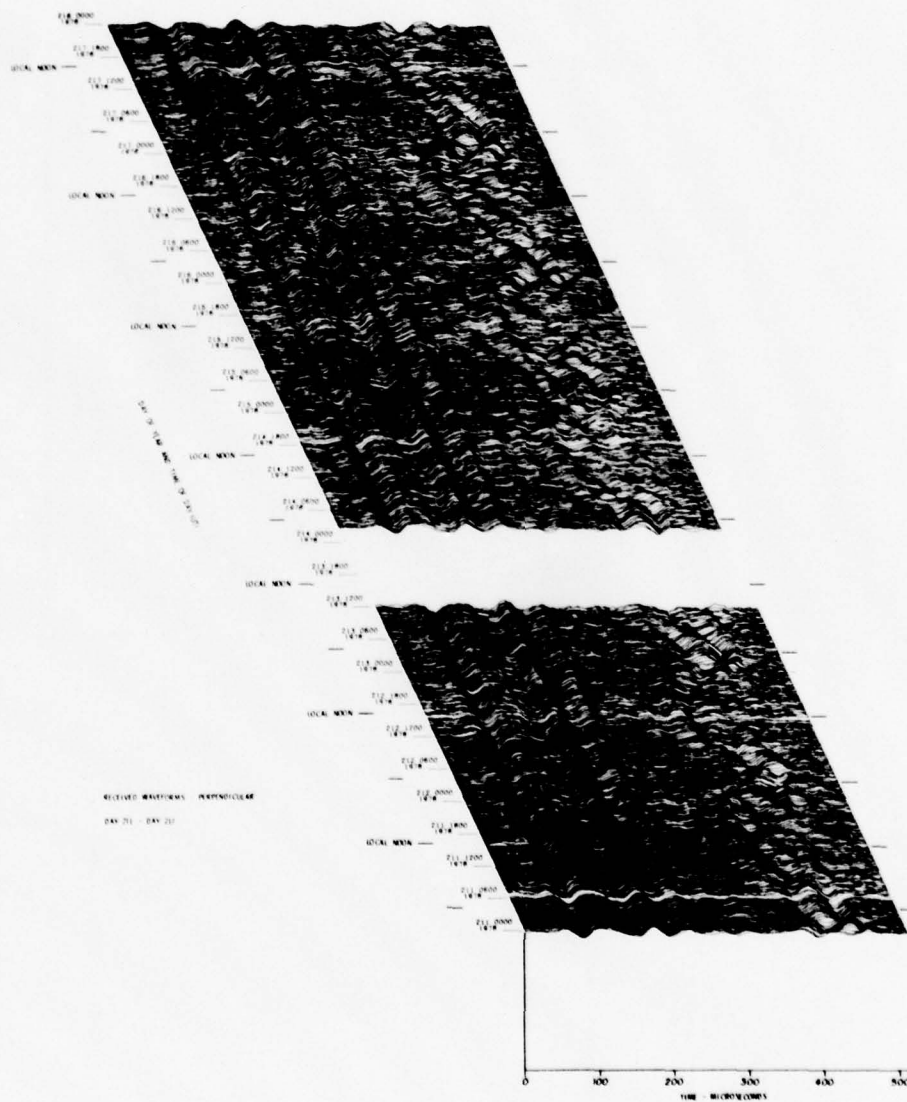


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 211 (30 Jul) - DAY 217 (5 Aug) 1978 (Cont)
 Part S. \perp Waveform Display

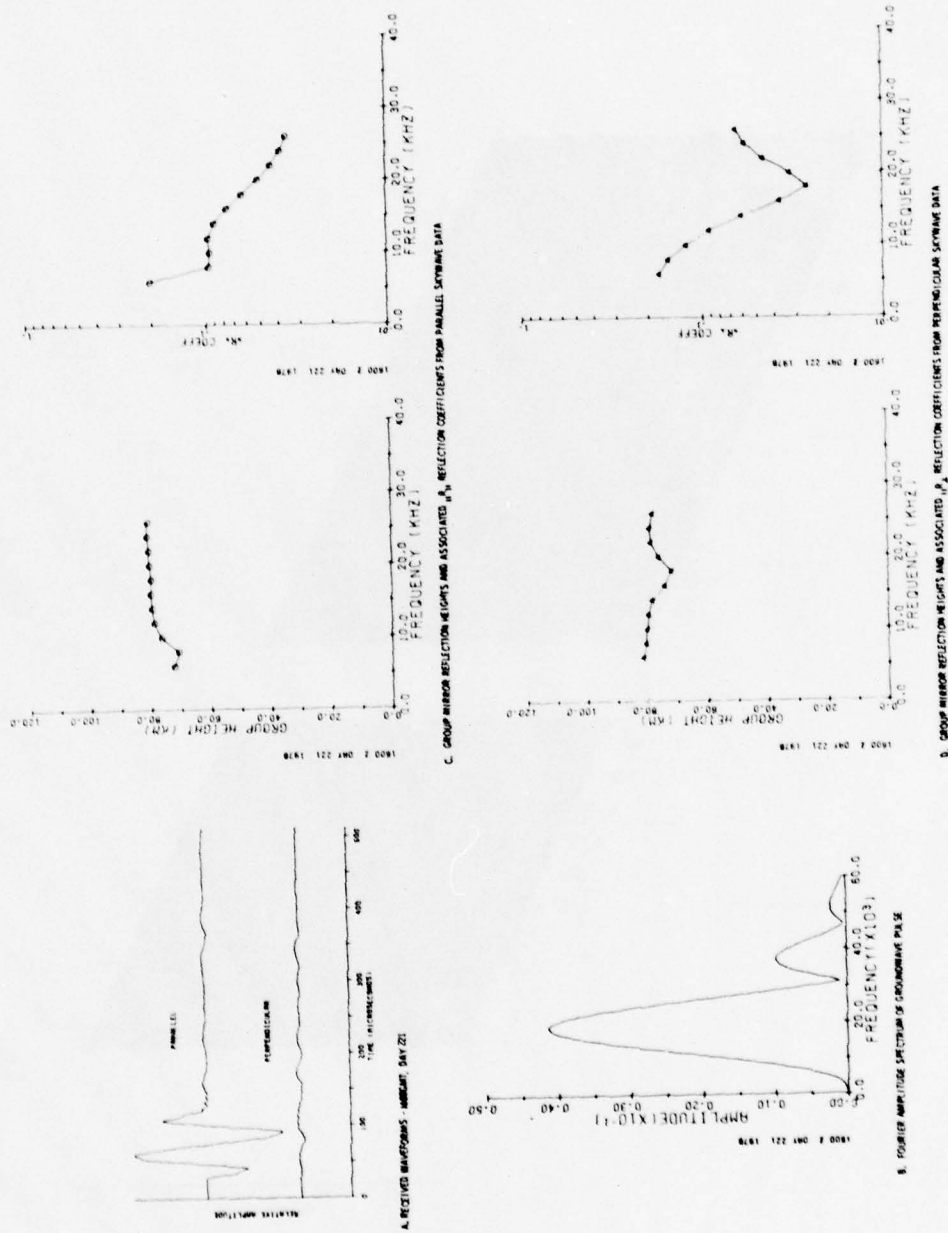


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 218 (6 Aug) - DAY 224 (12 Aug) 1978

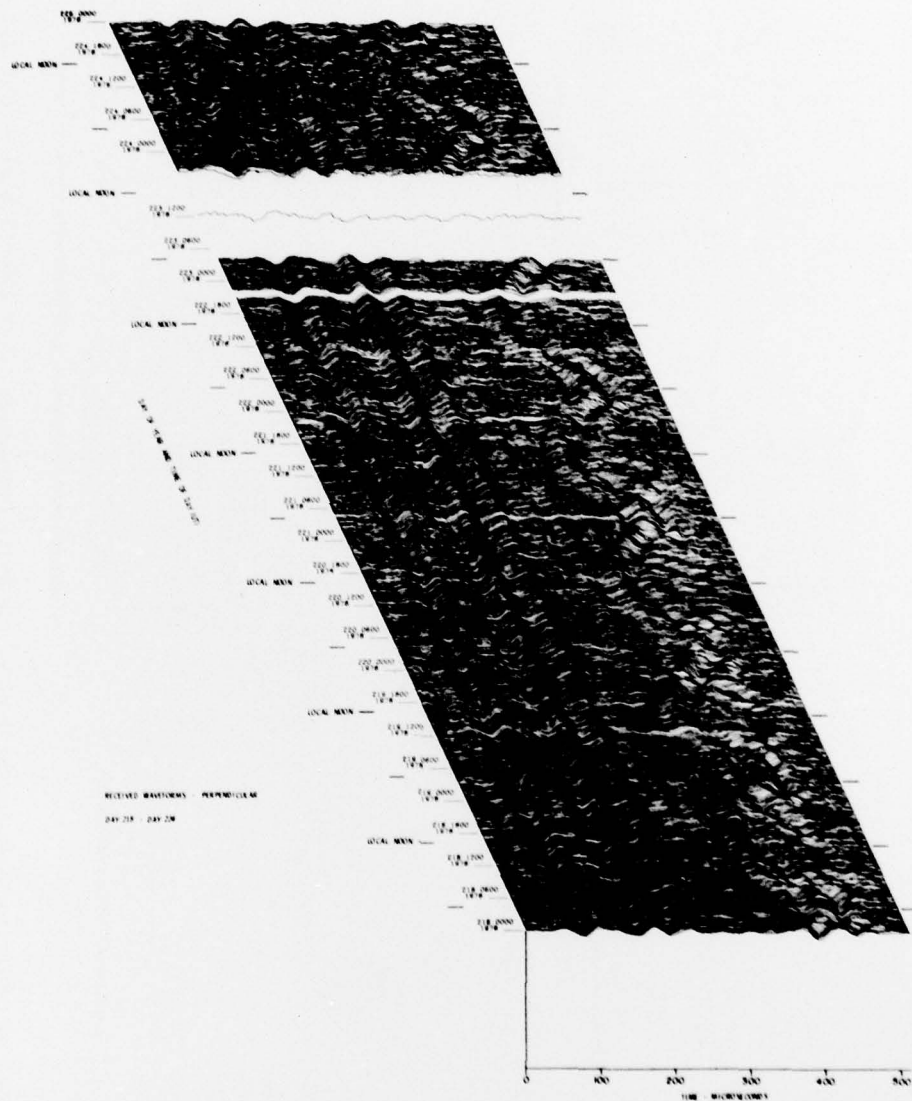


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 218 (6 Aug) - DAY 224 (12 Aug) 1978 (Cont)
 Part S. \perp Waveform Display

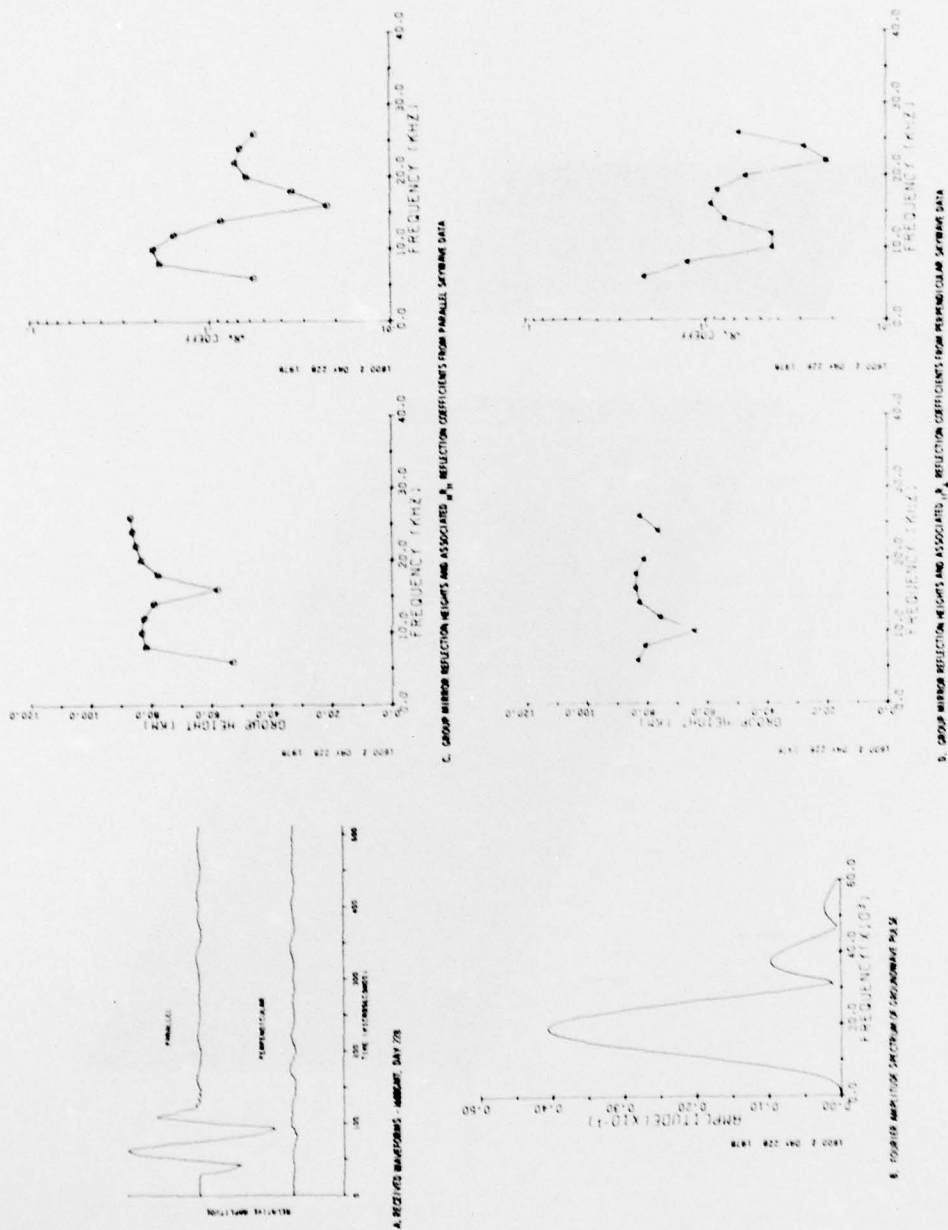


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 225 (13 Aug) - DAY 231 (19 Aug) 1978

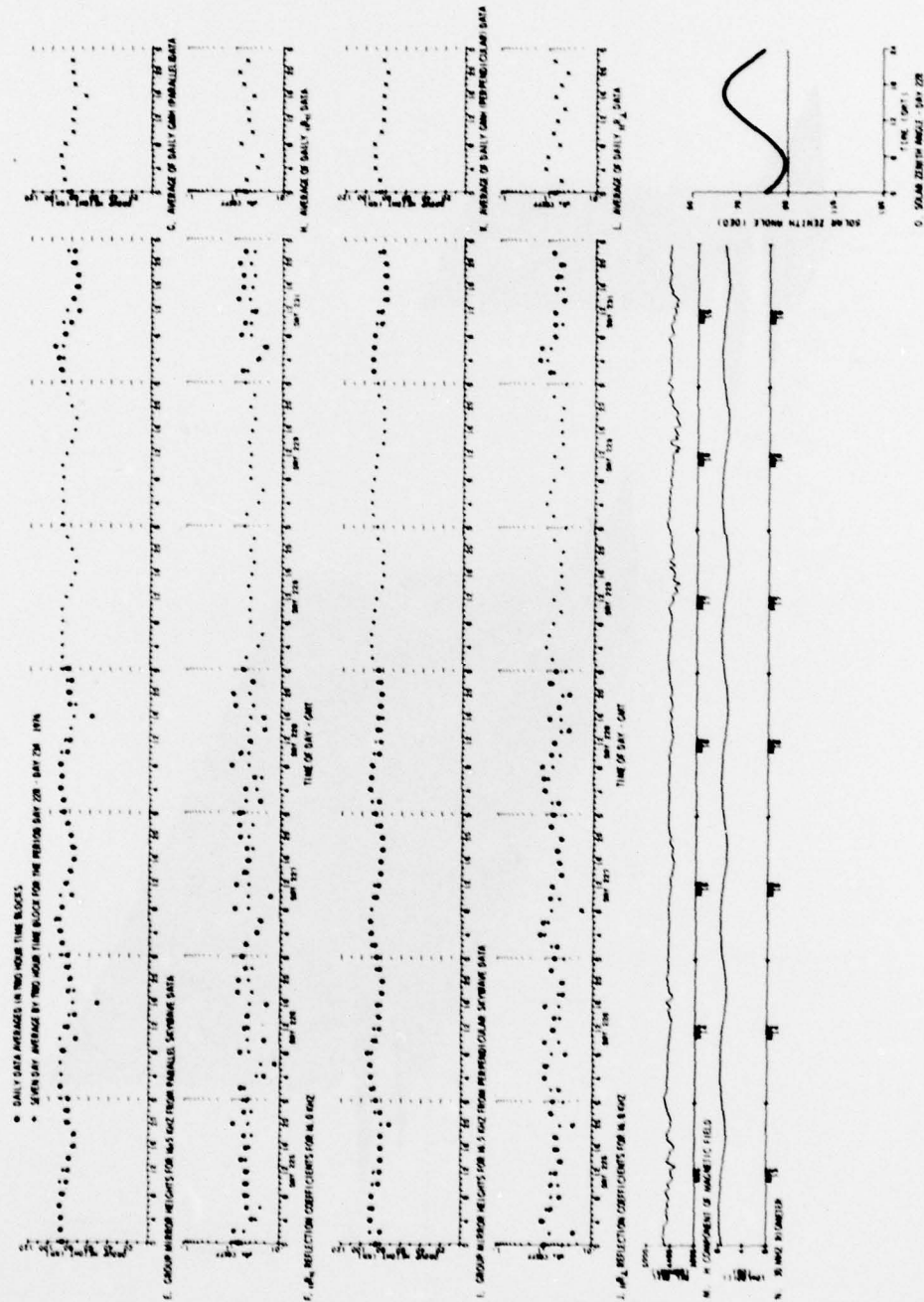


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 231 (19 Aug) 1978 (Cont)

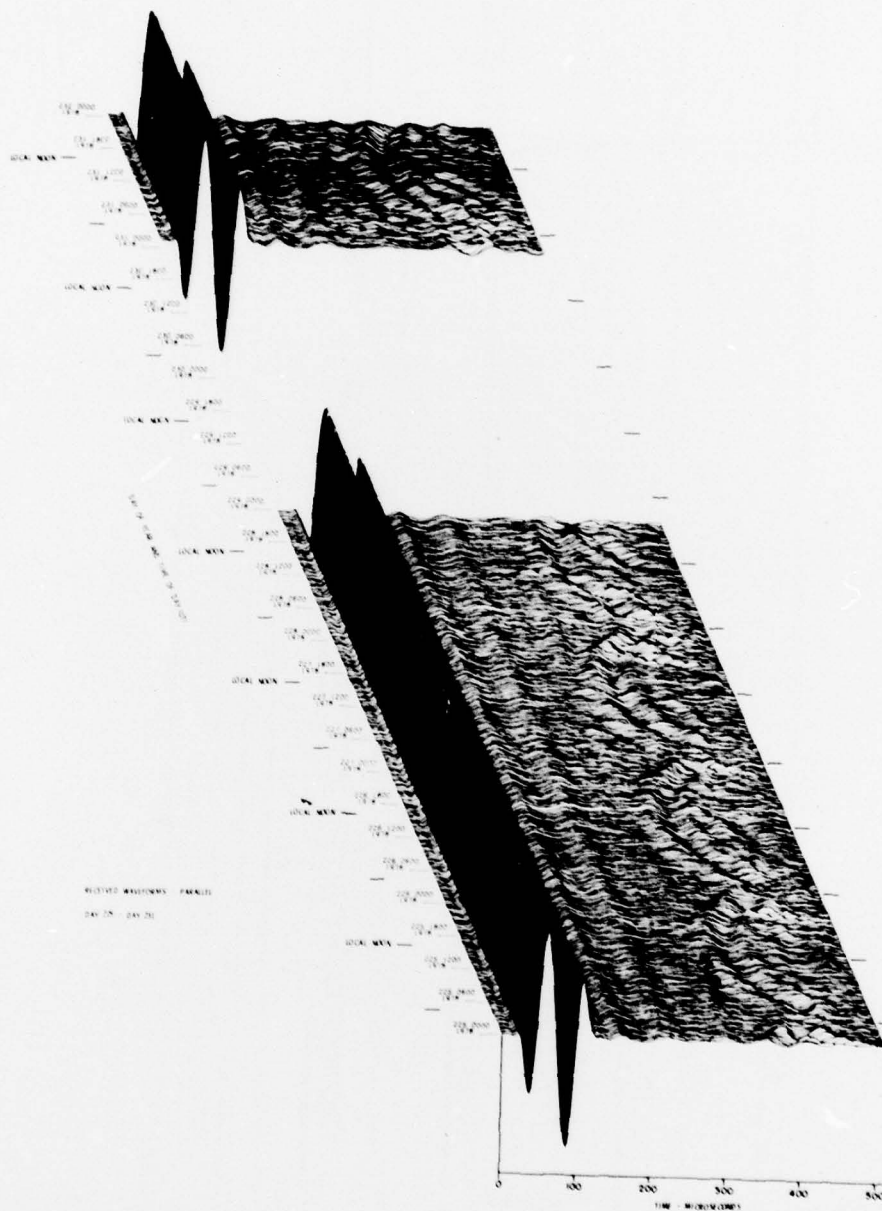


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 225 (13 Aug) - DAY 231 (19 Aug) 1978 (Cont)
 Part R. II Waveform Display

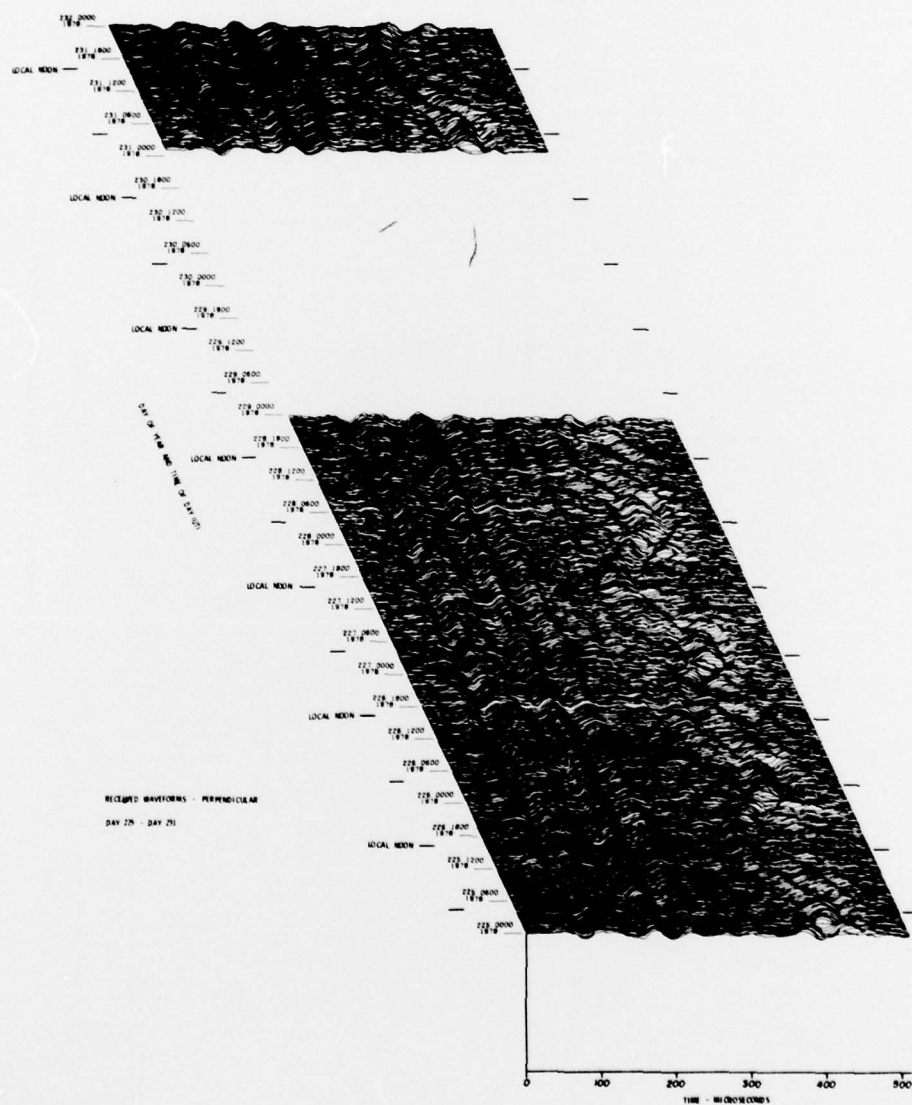


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 225 (13 Aug) - DAY 231 (19 Aug) 1978 (Cont)
 Part S. \perp Waveform Display

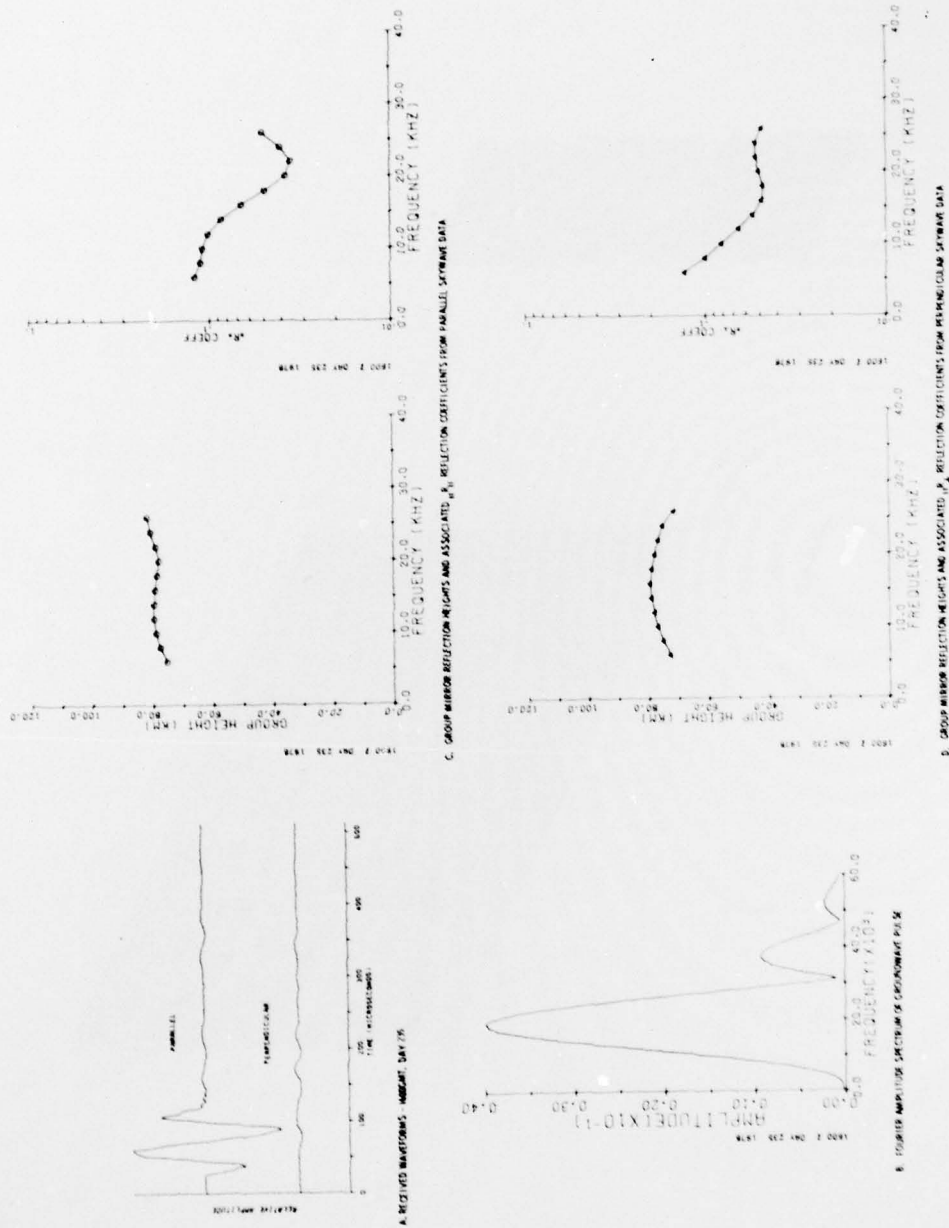


Figure 20. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 232 (20 Aug) - DAY 238 (26 Aug) 1978

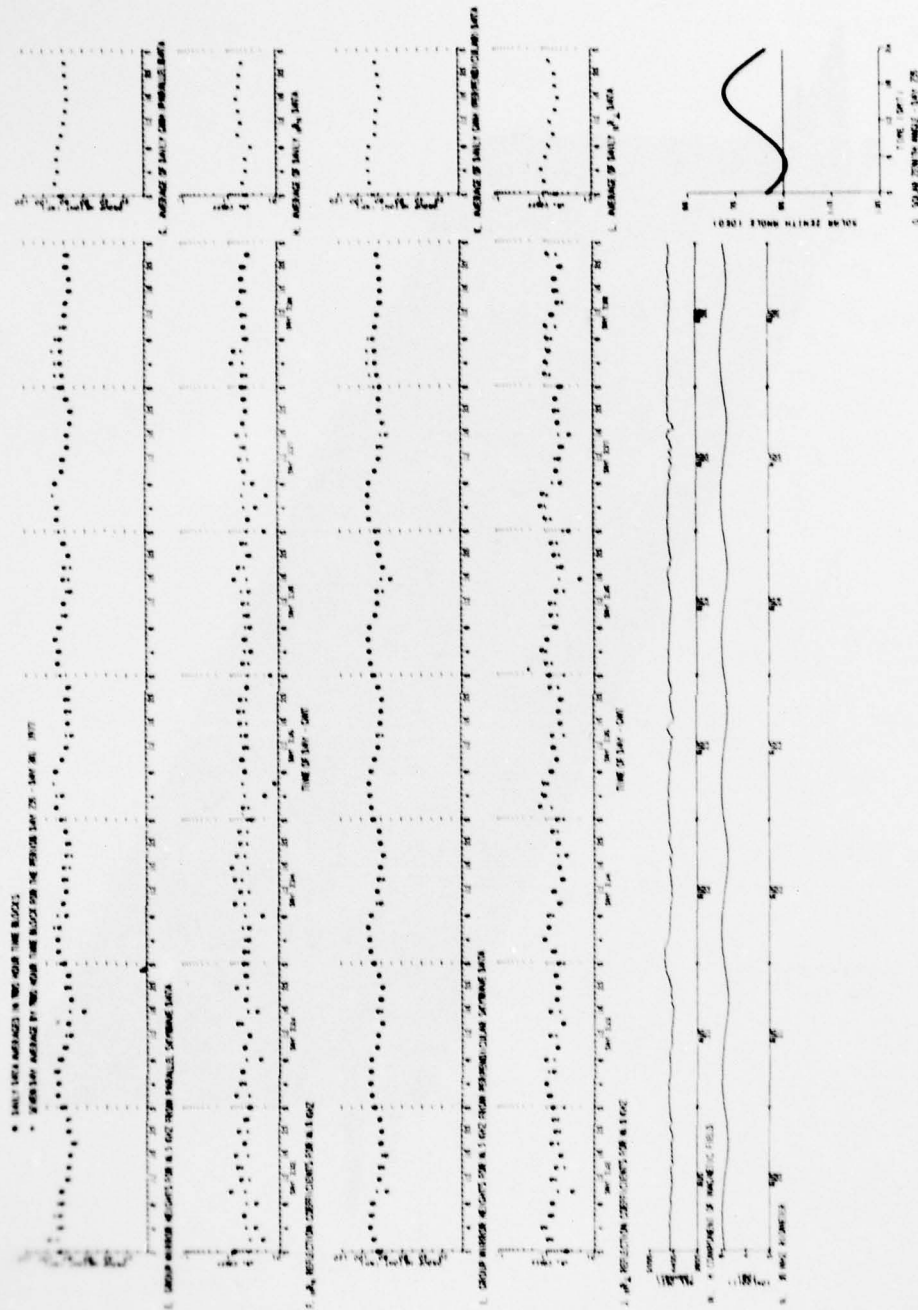


Figure 20. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 232 (20 Aug) - DAY 238 (26 Aug) 1978 (Cont)

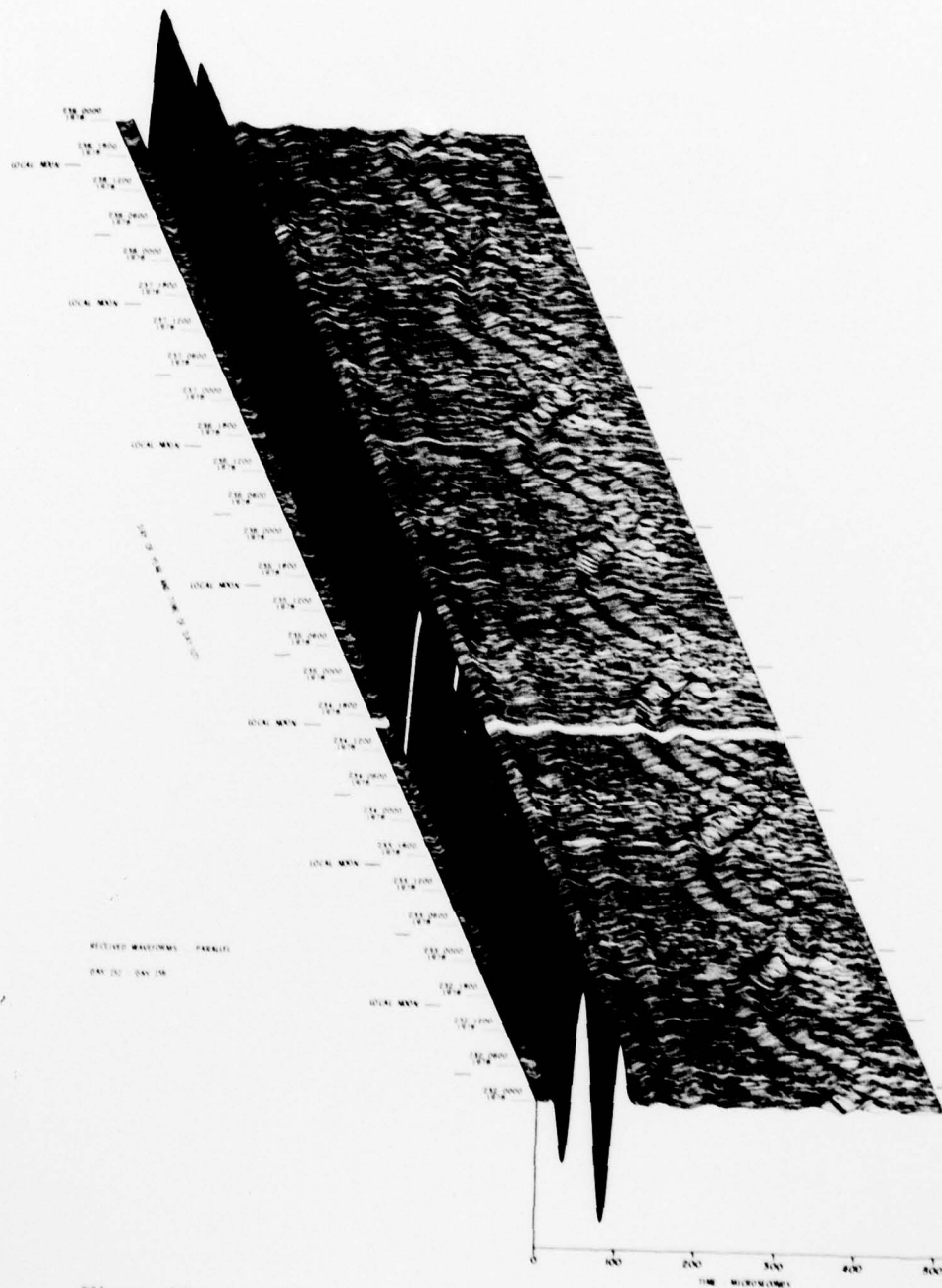


Figure 20. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 232 (20 Aug) - DAY 238 (26 Aug) 1978 (Cont)
 Part R. II Waveform Display

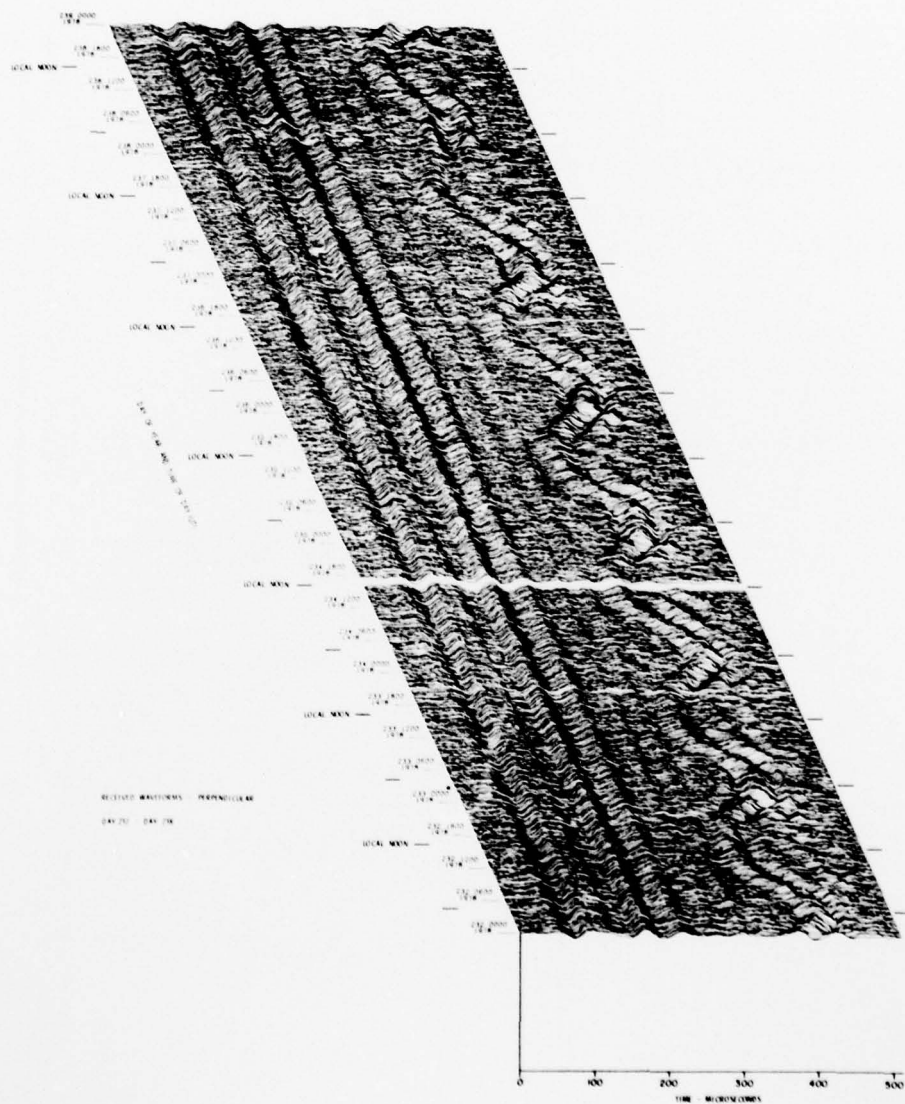
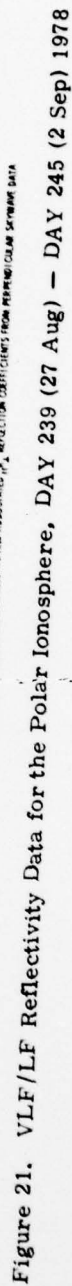


Figure 20. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 232 (20 Aug) - DAY 238 (26 Aug) 1978 (Cont)
 Part S. \perp Waveform Display



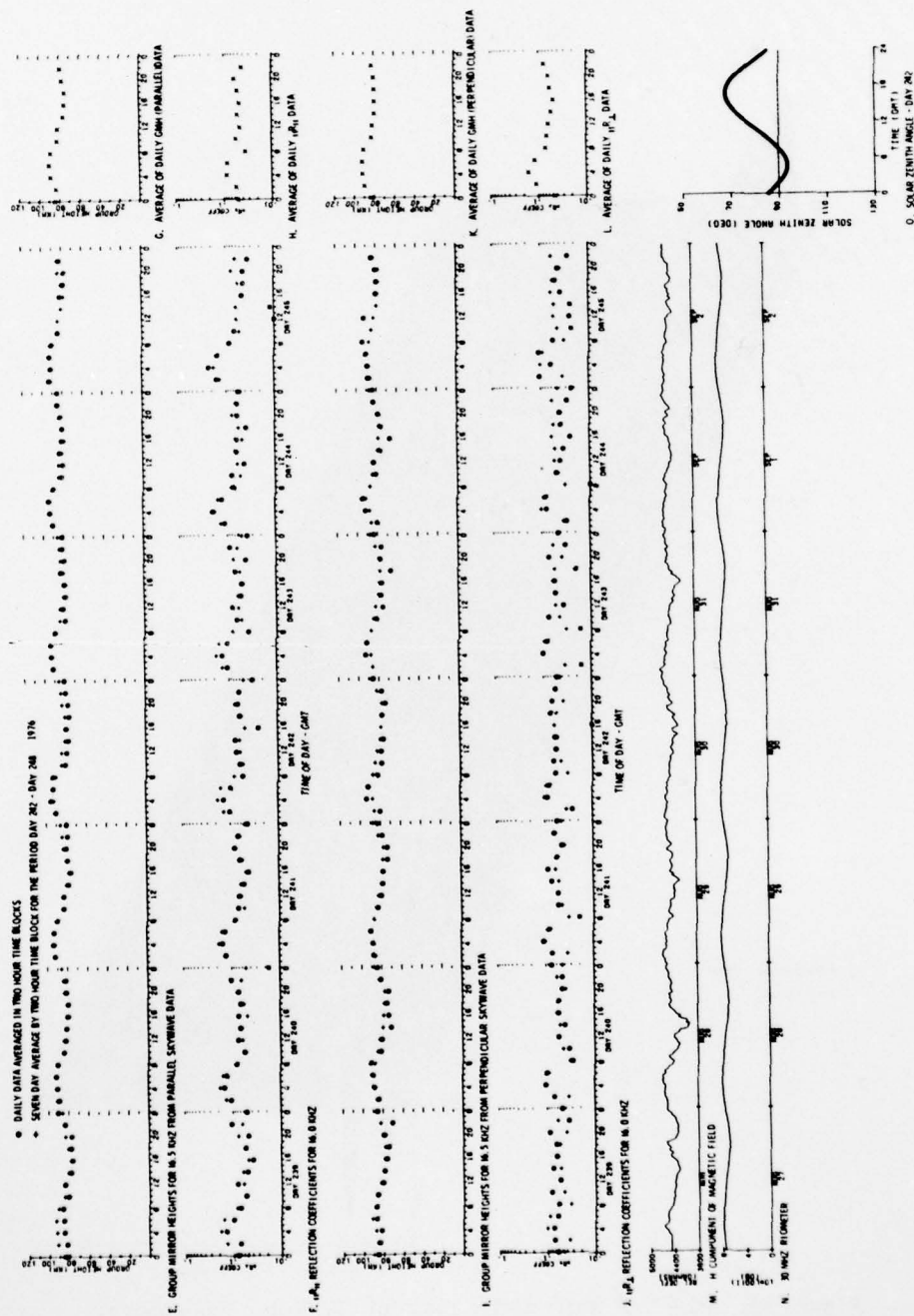


Figure 21. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 245 (2 Sep) 1978 (Cont)

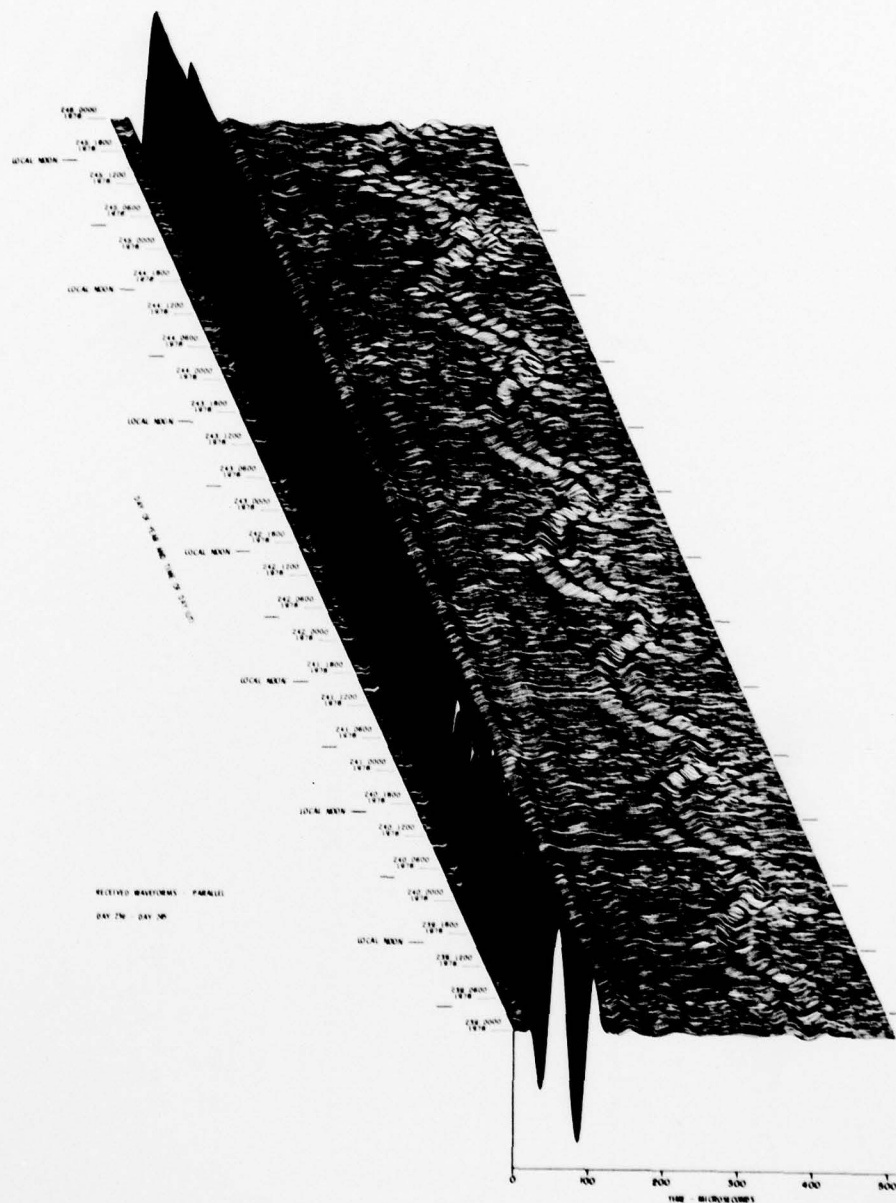


Figure 21. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 239 (27 Aug) - DAY 245 (2 Sep) 1978 (Cont)
 Part R. II Waveform Display

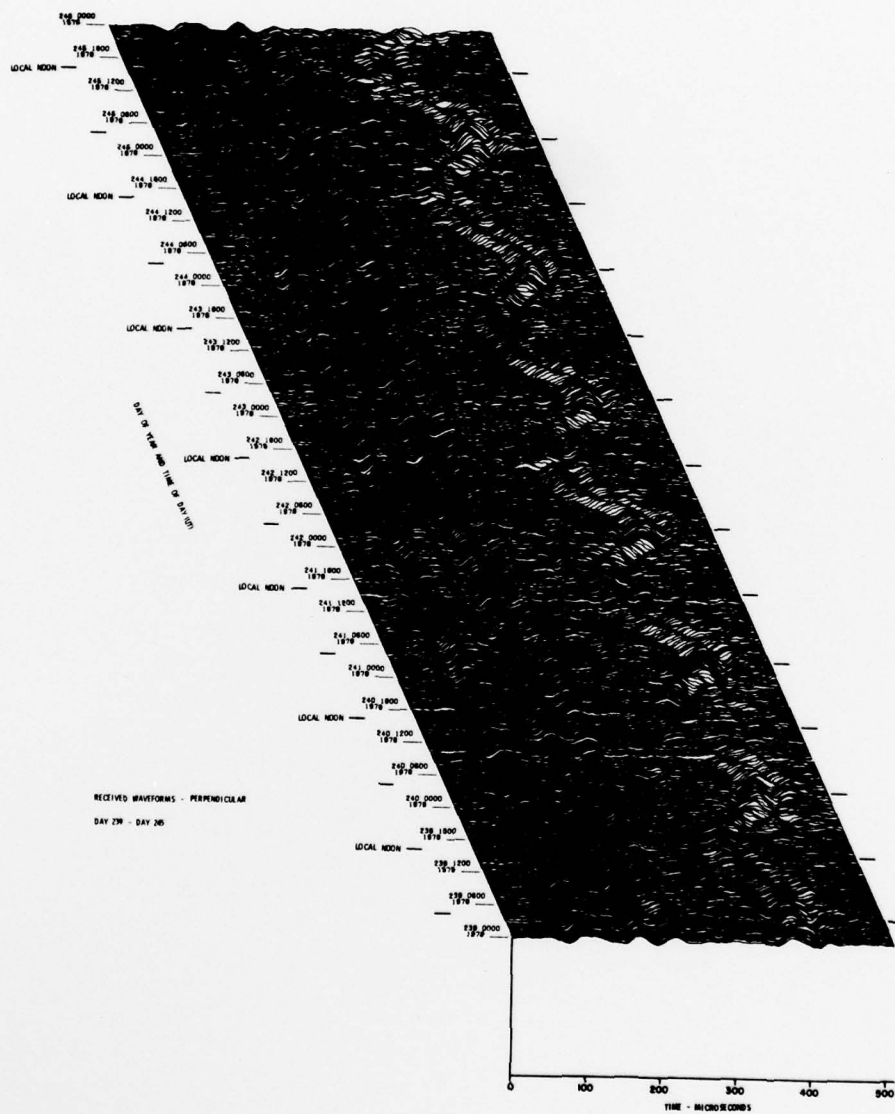


Figure 21. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 239 (27 Aug) - DAY 245 (2 Sep) 1978 (Cont)
Part S. \perp Waveform Display



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